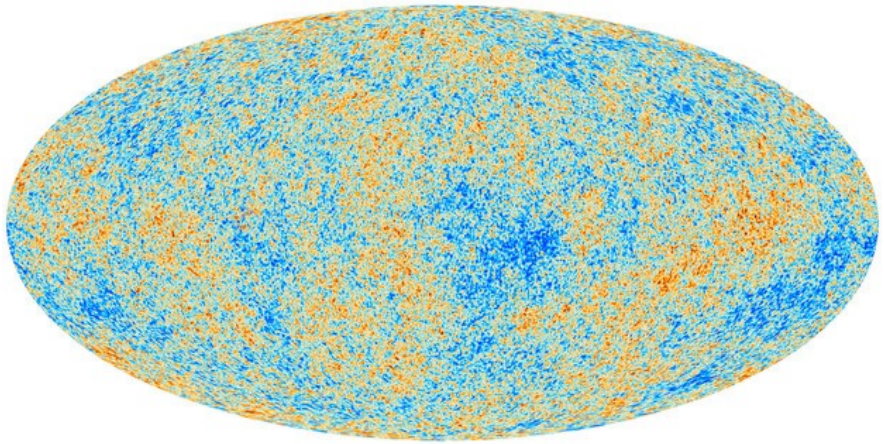
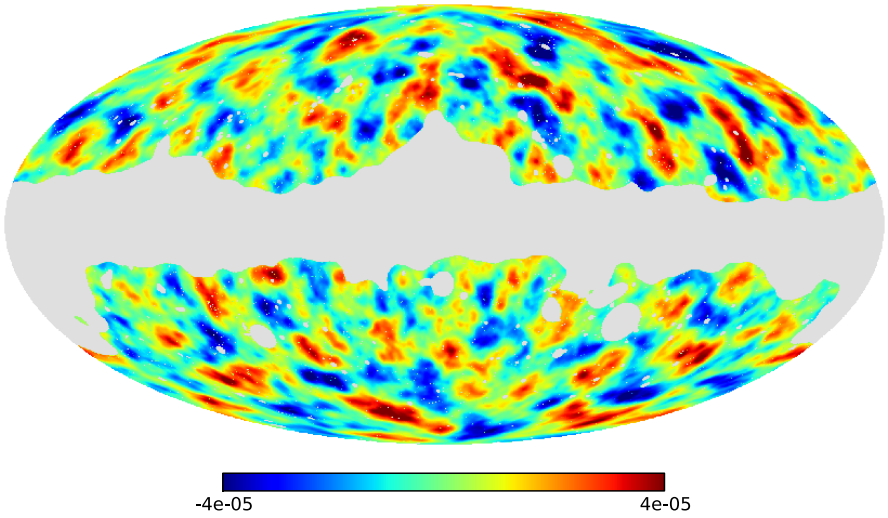
Cosmology from the *Planck* 2- and 4-pt functions

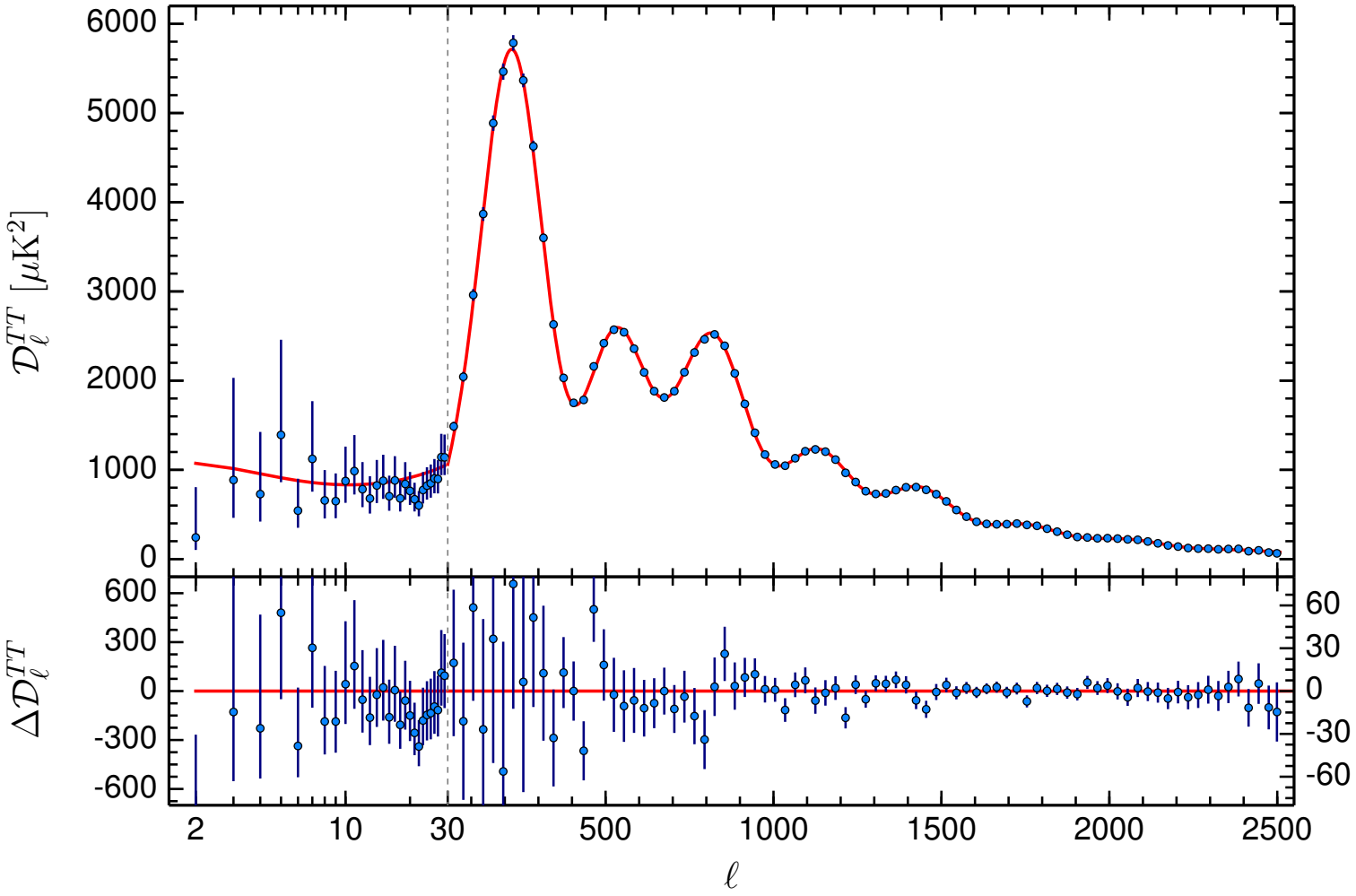
Anthony Challinor on behalf of the *Planck* Collaboration





KICC/IoA/DAMTP
University of Cambridge

Planck 2014 *TT*

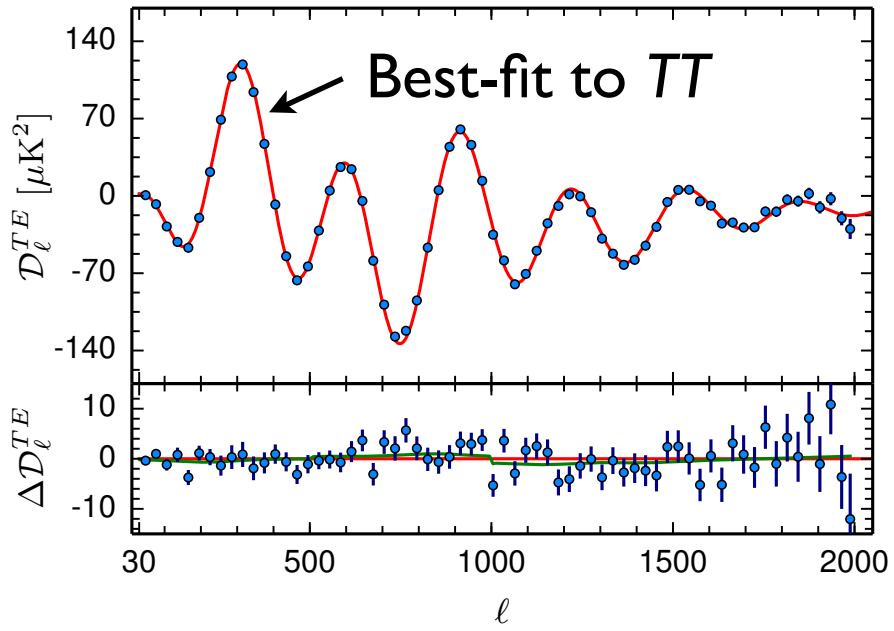


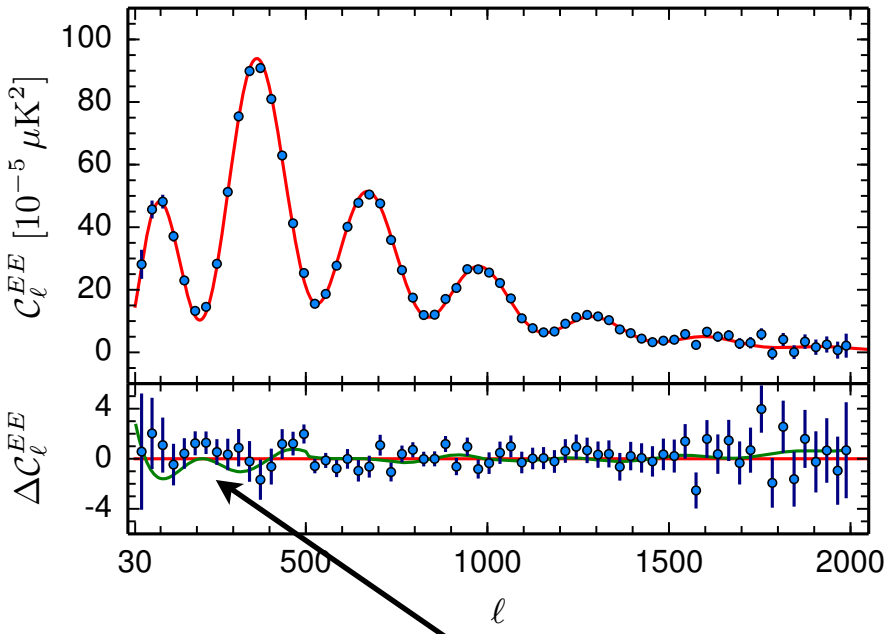
Preliminary

Main data changes from 2013

- Data from full mission (including polarization)
- Better filtering to reduce l=1800 '4K cooler' feature
- Improved absolute calibration (orbital dipole)
- Improvements to beams
- Increased sky fractions
- Correlated noise identified between detsets
  - Now use cross-half-mission spectra as baseline but only small impact on parameters
- Changes to foreground model (and no high-l experiments used directly now)

Planck 2014 *TE* and *EE*

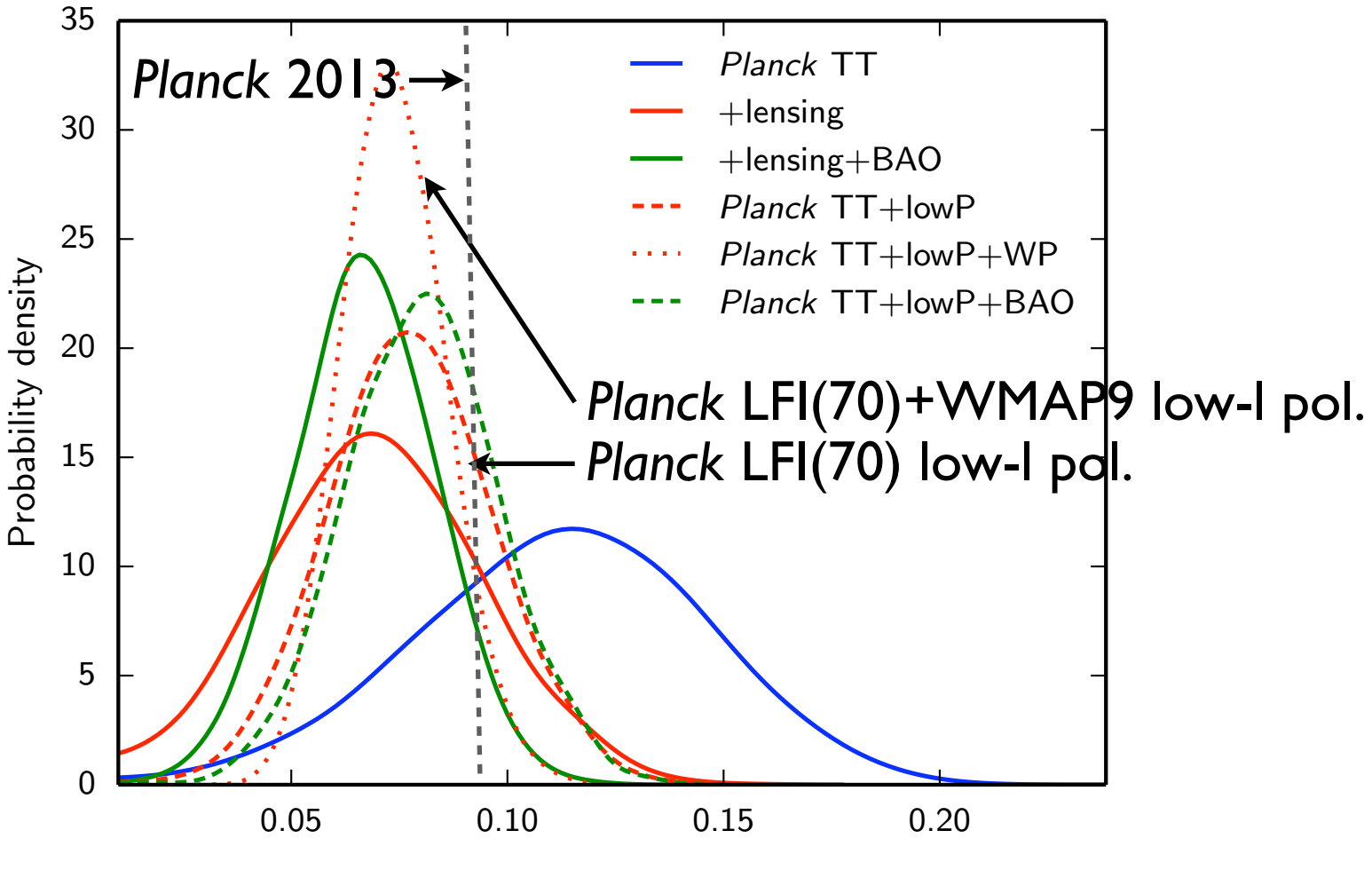




Beware: low-level systematics still in polarization spectra

Preliminary

Reionization from lowP

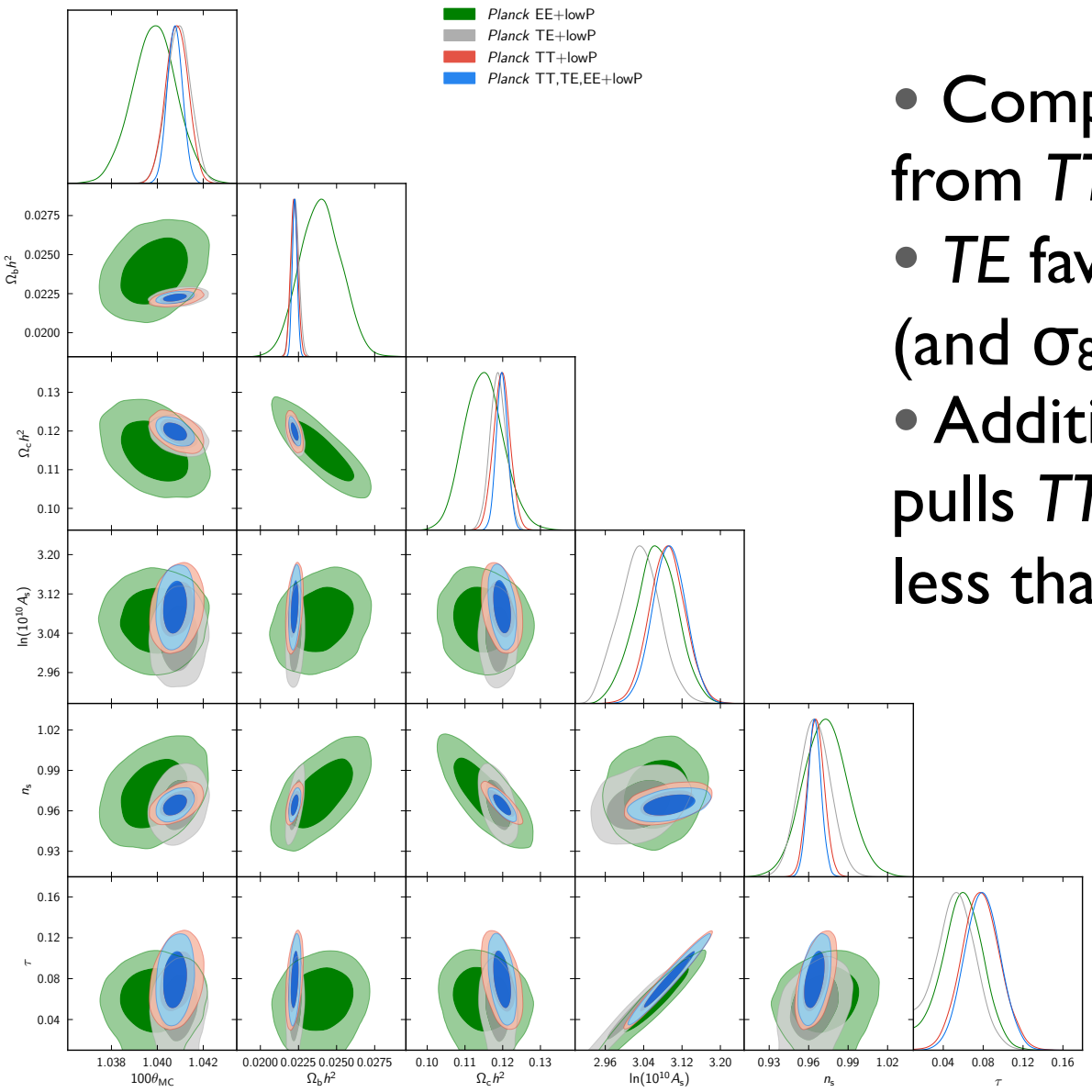


$$\tau = 0.078^{+0.019}_{-0.019} \quad (Planck\ \mathrm{TT{+}lowP};\ 68\%)$$

Preliminary

$$\tau = 0.074^{+0.011}_{-0.013} \quad (Planck\ \mathrm{TT{+}lowP{+}WP};\ 68\%)$$

Consistent LCDM from *T* and *P*



- Comparable precision from *TT* or *TE* (*EE* noisy)
- *TE* favours lower τ, A_s (and σ_8)
- Addition of polarization pulls *TT* best-fit params by less than 0.2σ

Preliminary

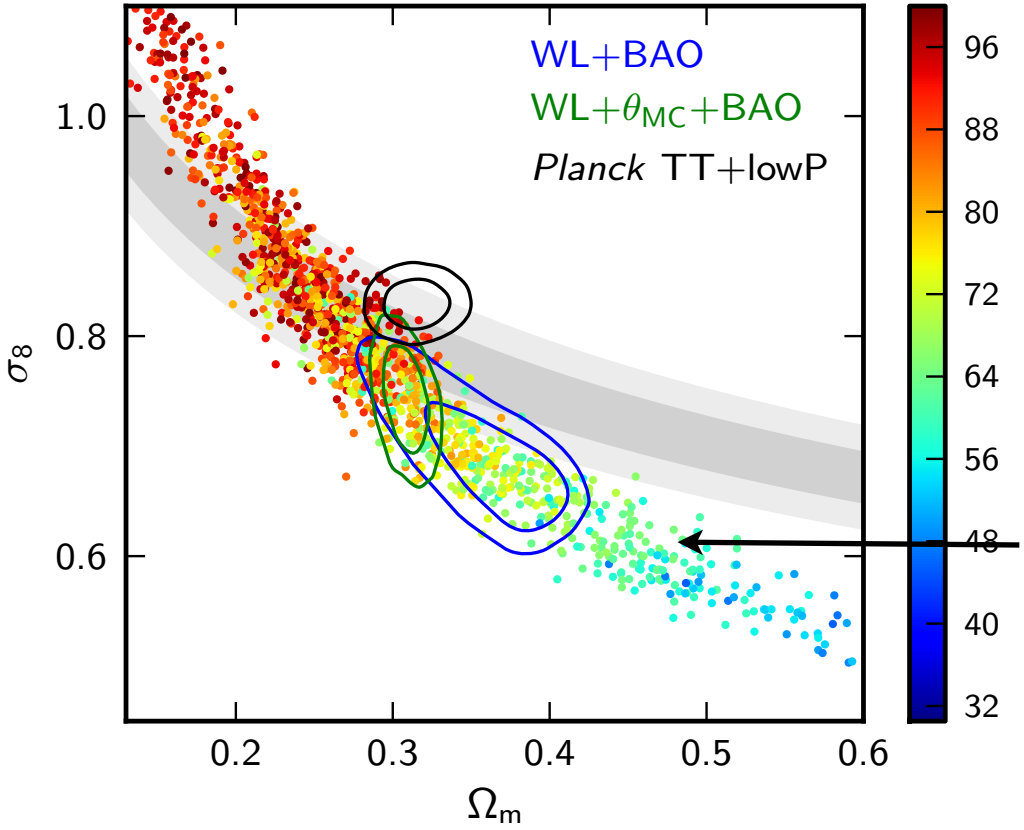
2013 TT+WP c.f. 2014 TT+lowP

Parameter	2013N(DS)	2014 TT+lowP	(2013-2014)/σ(2013)
$100\theta_{MC}$	1.04131±0.00063	1.04085±0.00047	0.7
$\Omega_b h^2$	0.02205±0.00028	0.02222±0.00023	-0.6
$\Omega_c h^2$	0.1199±0.0027	0.1197±0.0022	0.1
H_0	67.3±1.2	67.3±1.0	0
n_s	0.9603±0.0073	0.9655±0.0062	-0.7
Ω_m	0.315±0.017	0.315±0.013	0
σ_8	0.829±0.012	0.829±0.014	0
τ	0.089±0.013	0.078±0.019	0.8
$10^9 A_s e^{-2\tau}$	1.836±0.013	1.880±0.014	-3.4

Calibration

Preliminary

Possible LCDM tensions?



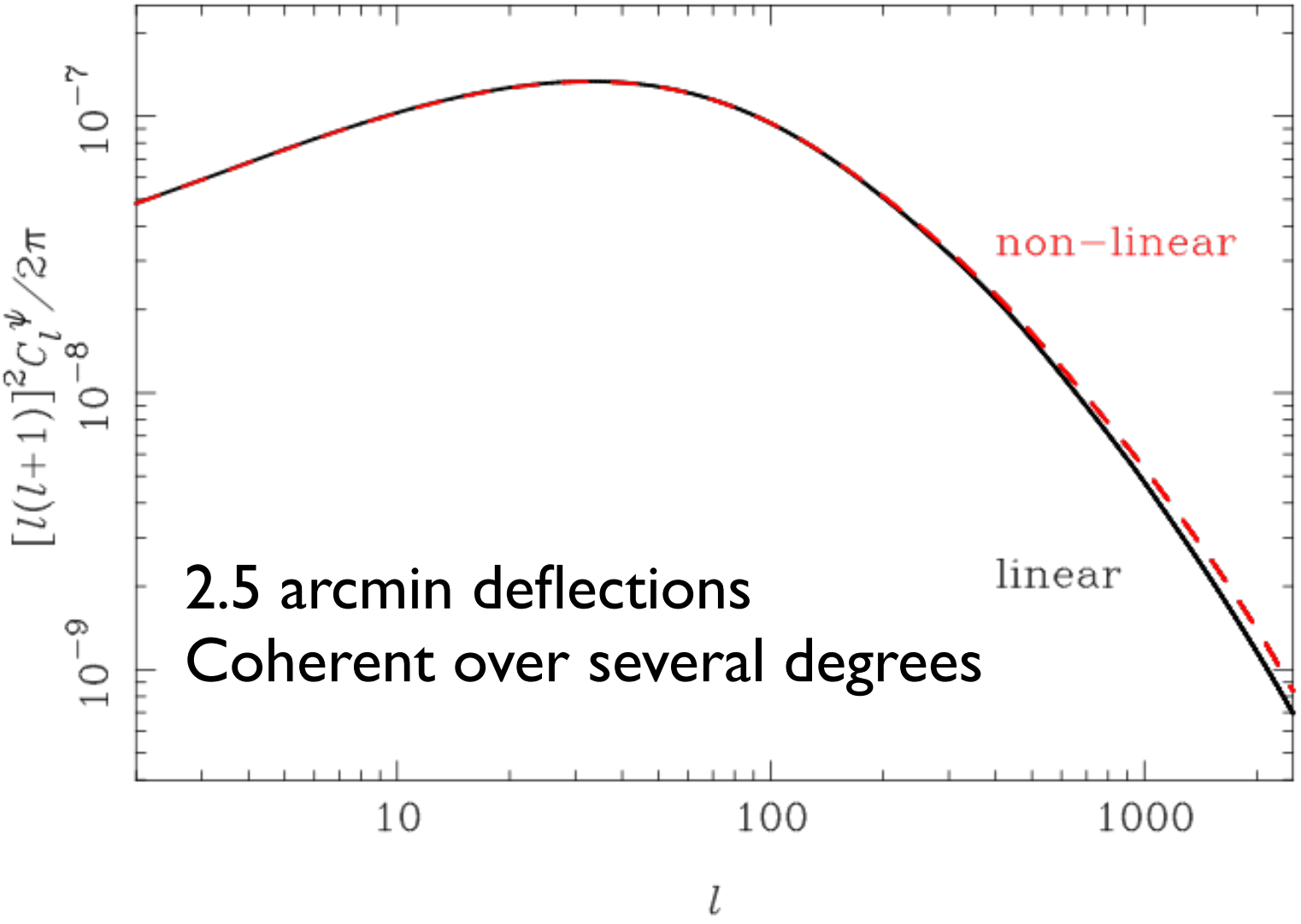
- Direct H_0
- *Planck* clusters
- Cosmic shear
- Redshift-space distortions

CFHTLenS `conservative' cut (Heymans+ 13)+ω_b+n_s priors

Can pull to new physics (e.g. $w \neq -1$, m_ν, modified gravity) in LCDM extensions

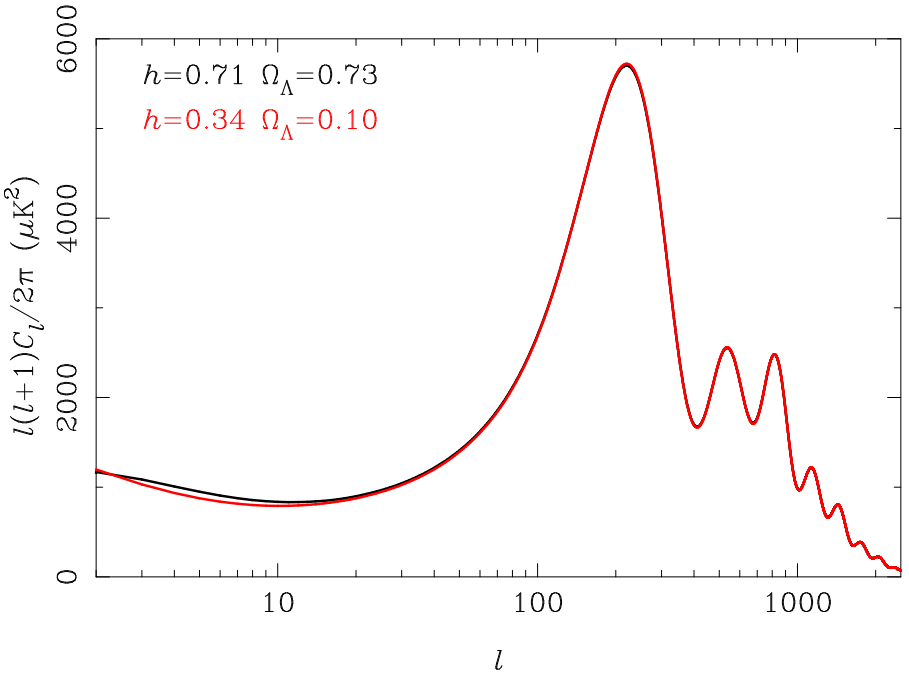
Preliminary

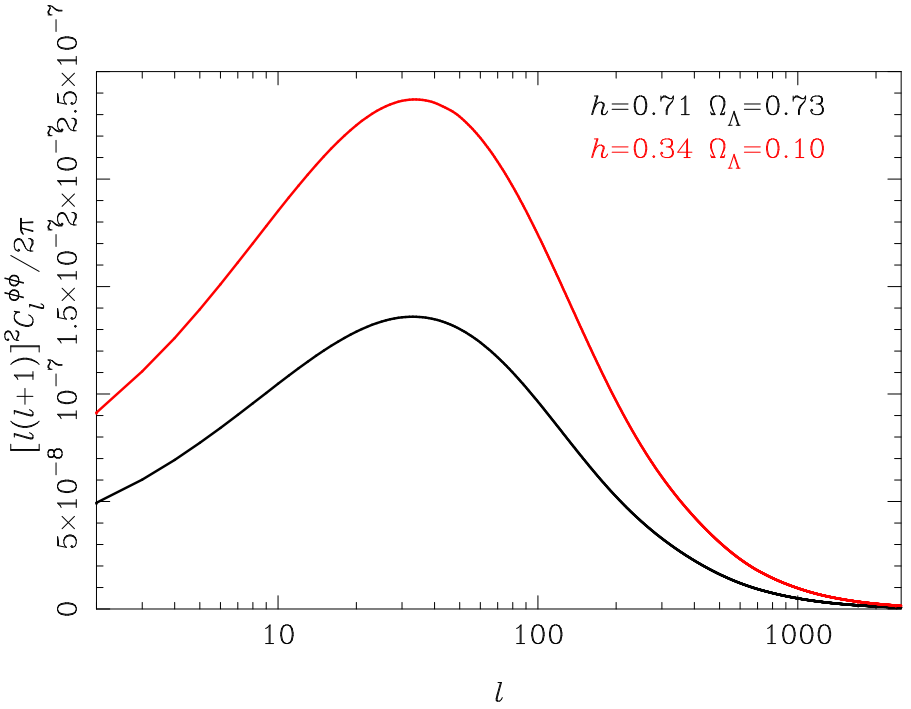
CMB lensing power spectrum



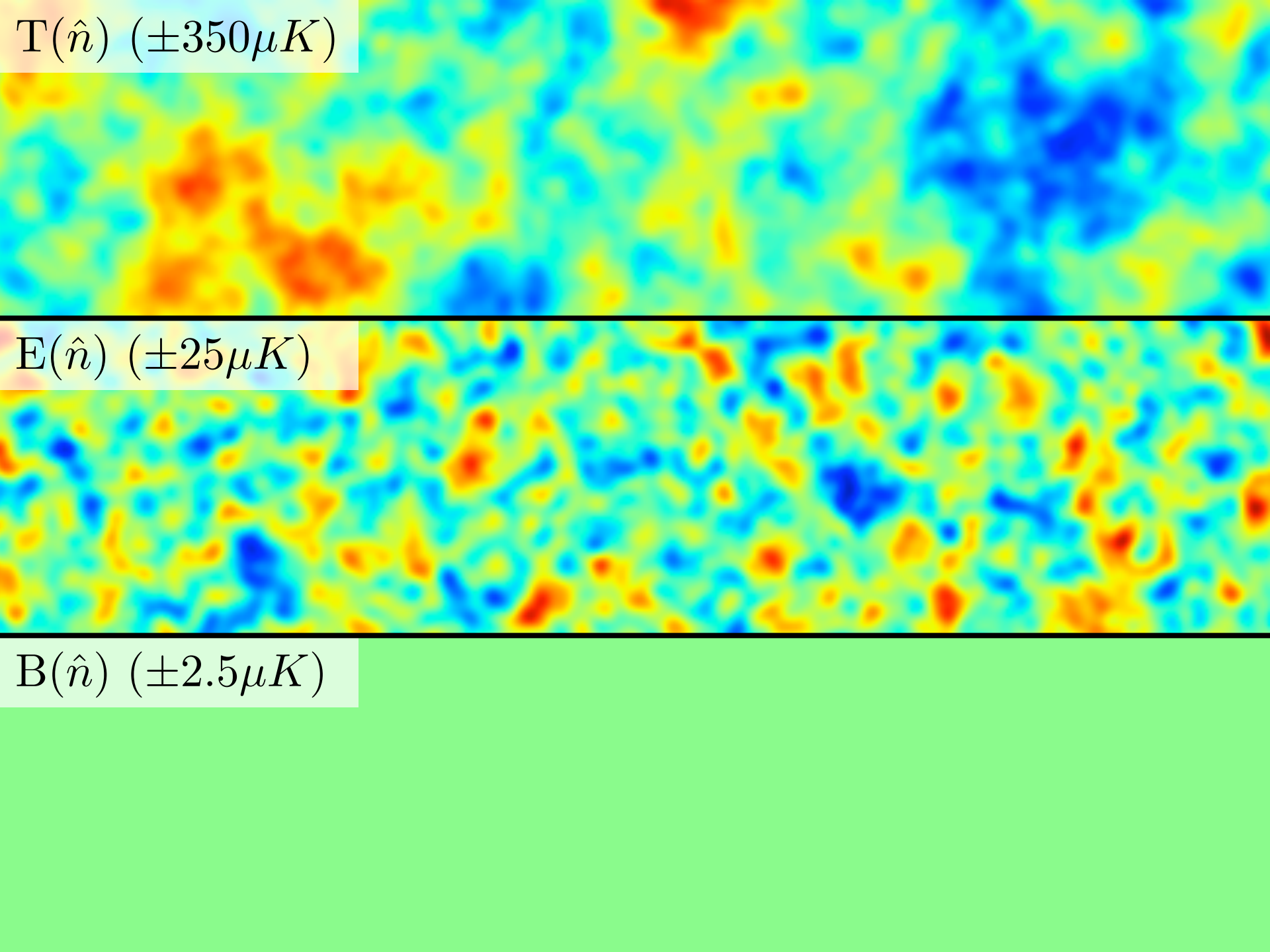
2.5 arcmin deflections
Coherent over several degrees

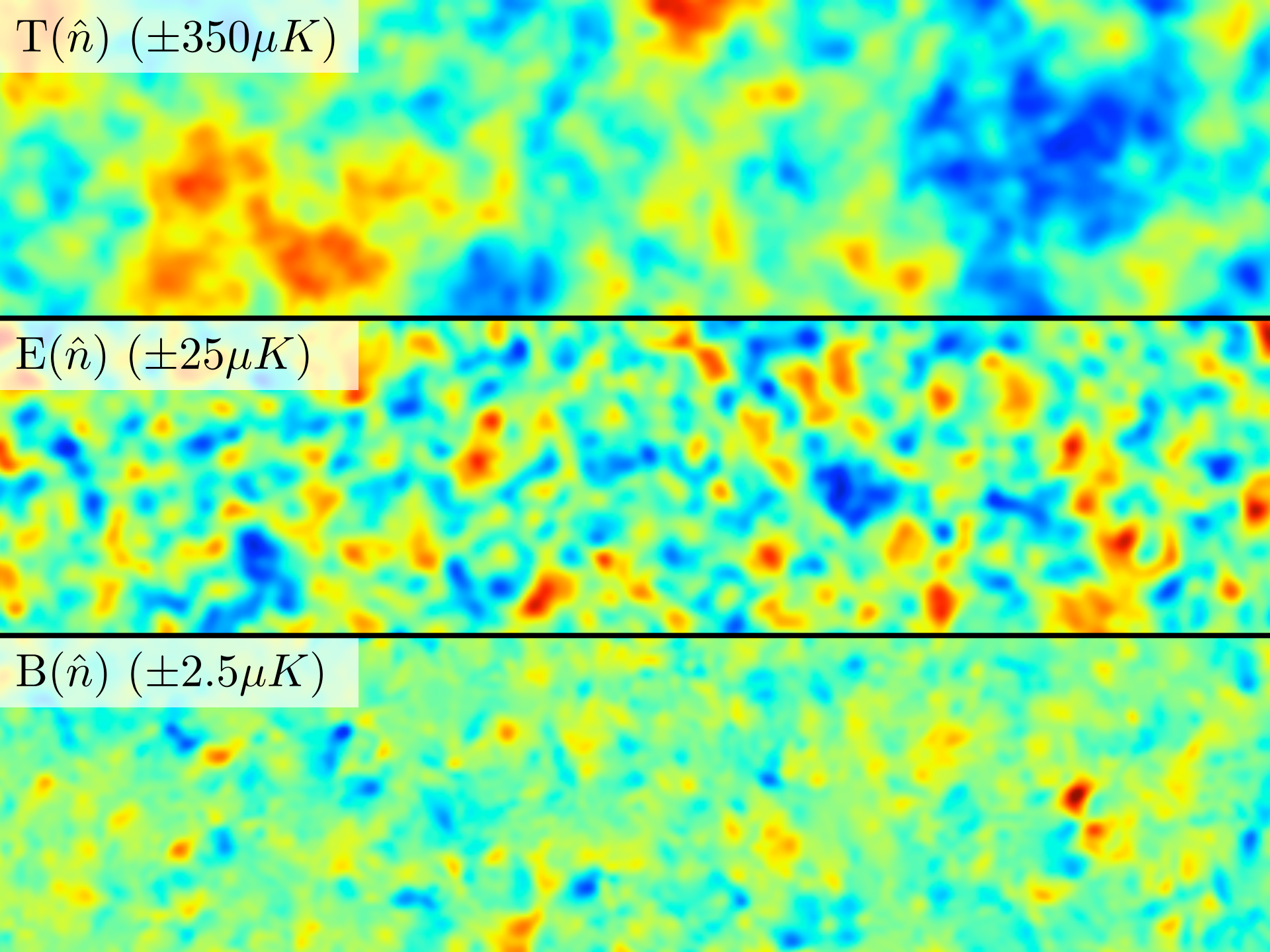
Dark params from CMB lensing





Geometric degeneracy in CMB power spectra broken by different amounts of lensing in models with same $D_A(z_*)$

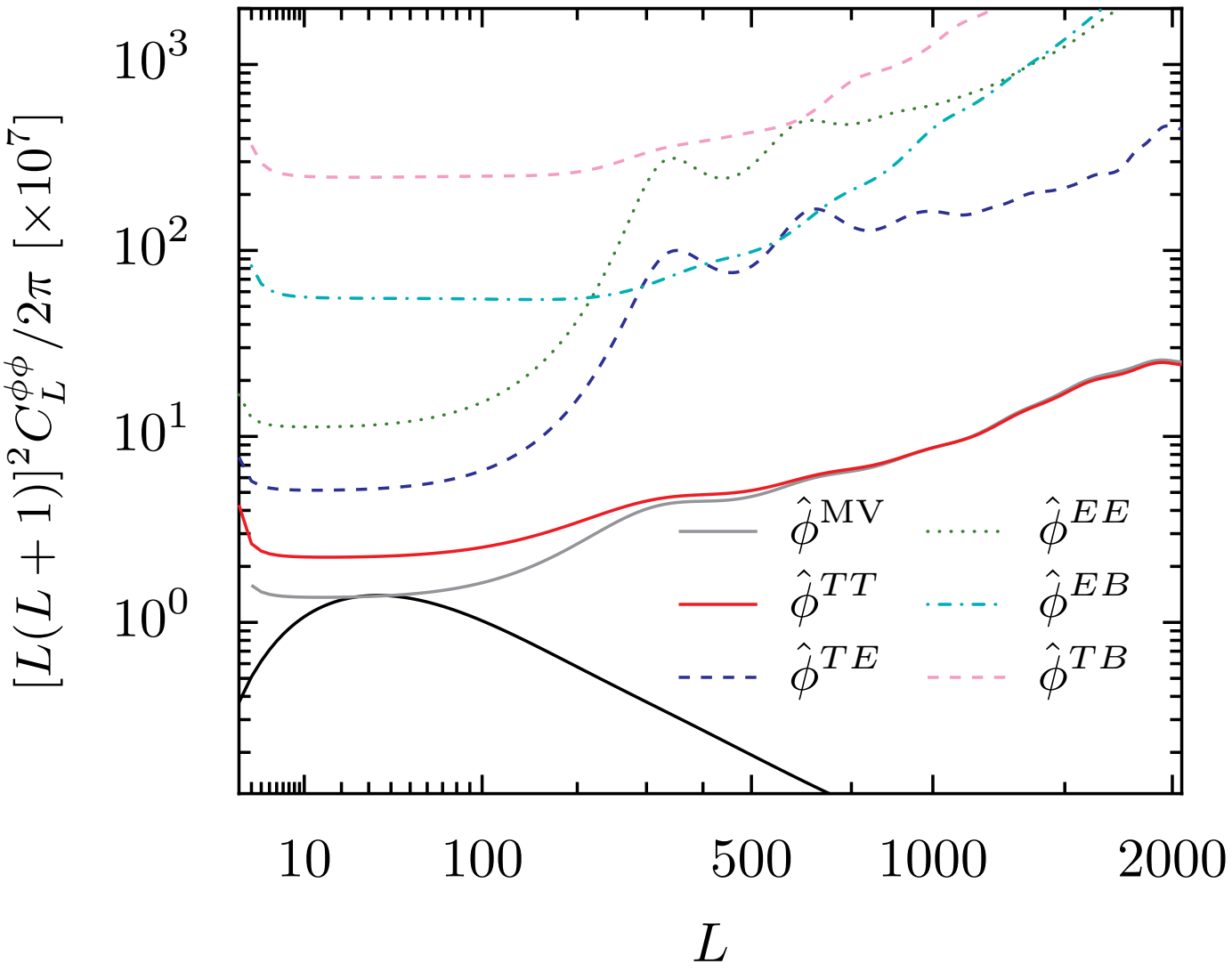

$\mathrm{T}(\hat{n})\ (\pm 350\mu K)$
$\mathrm{E}(\hat{n})\ (\pm 25\mu K)$
$\mathrm{B}(\hat{n})\ (\pm 2.5\mu K)$


$\mathrm{T}(\hat{n})\ (\pm 350\mu K)$
$\mathrm{E}(\hat{n})\ (\pm 25\mu K)$
$\mathrm{B}(\hat{n})\ (\pm 2.5\mu K)$

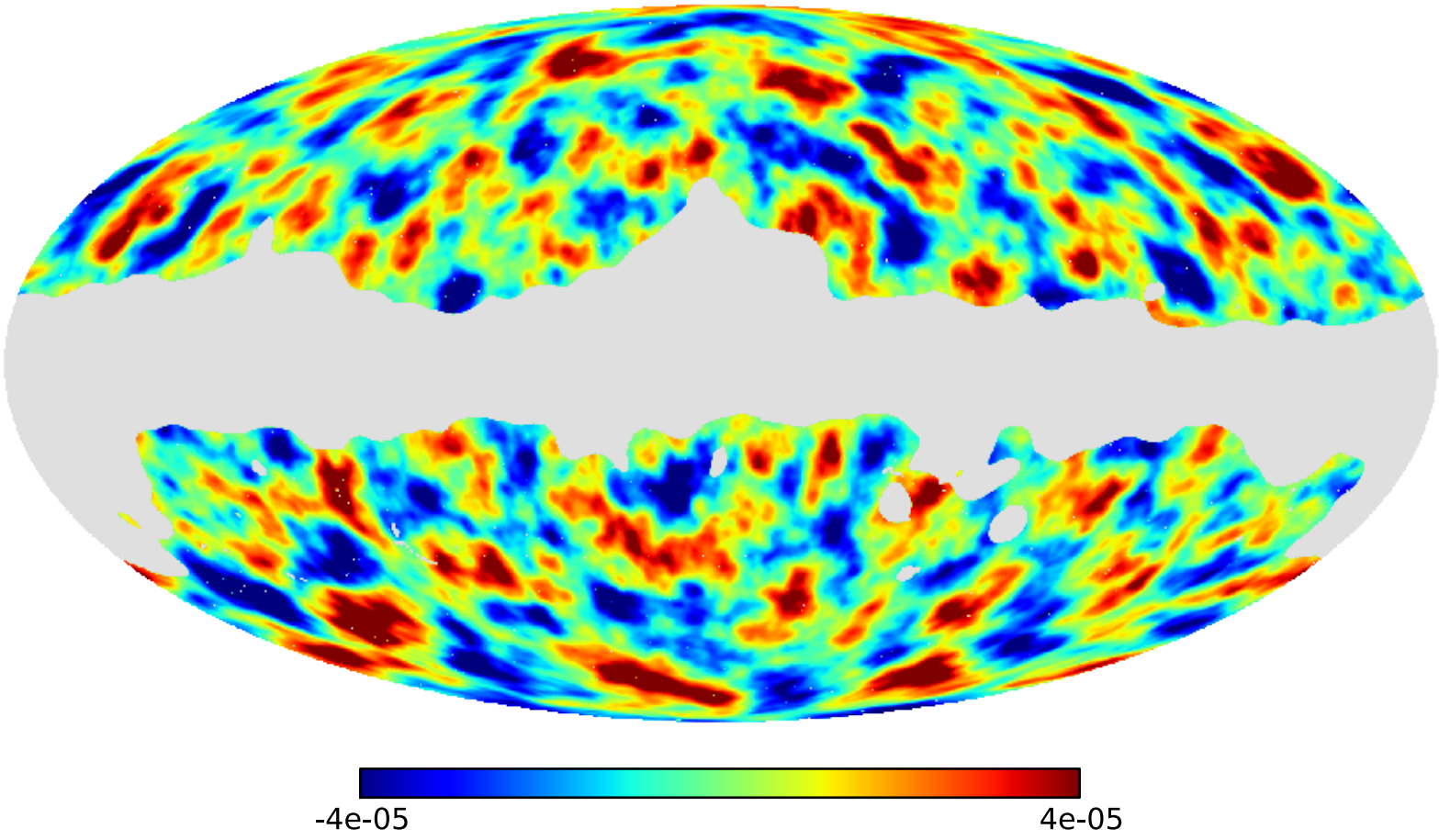
Main improvements over 2013

- Error bars reduced by nearly factor of two
  - Twice as much *T* data + new polarization
- Full set of lensing estimators (*TT*, *TE*, *EE*, *TB*, *EB* and MV)
  - Crosses between estimators give 15 C_l estimators
- SMICA component-separated maps (67.3% of sky)
- Many analysis improvements
  - Improved likelihood ($N^{(1)}$ theory dependence, faster)
  - New consistency and null tests
    - ⋆ Internal consistency of *T* and *P* estimators
    - ⋆ Half-mission null tests and HM1×HM2 estimators

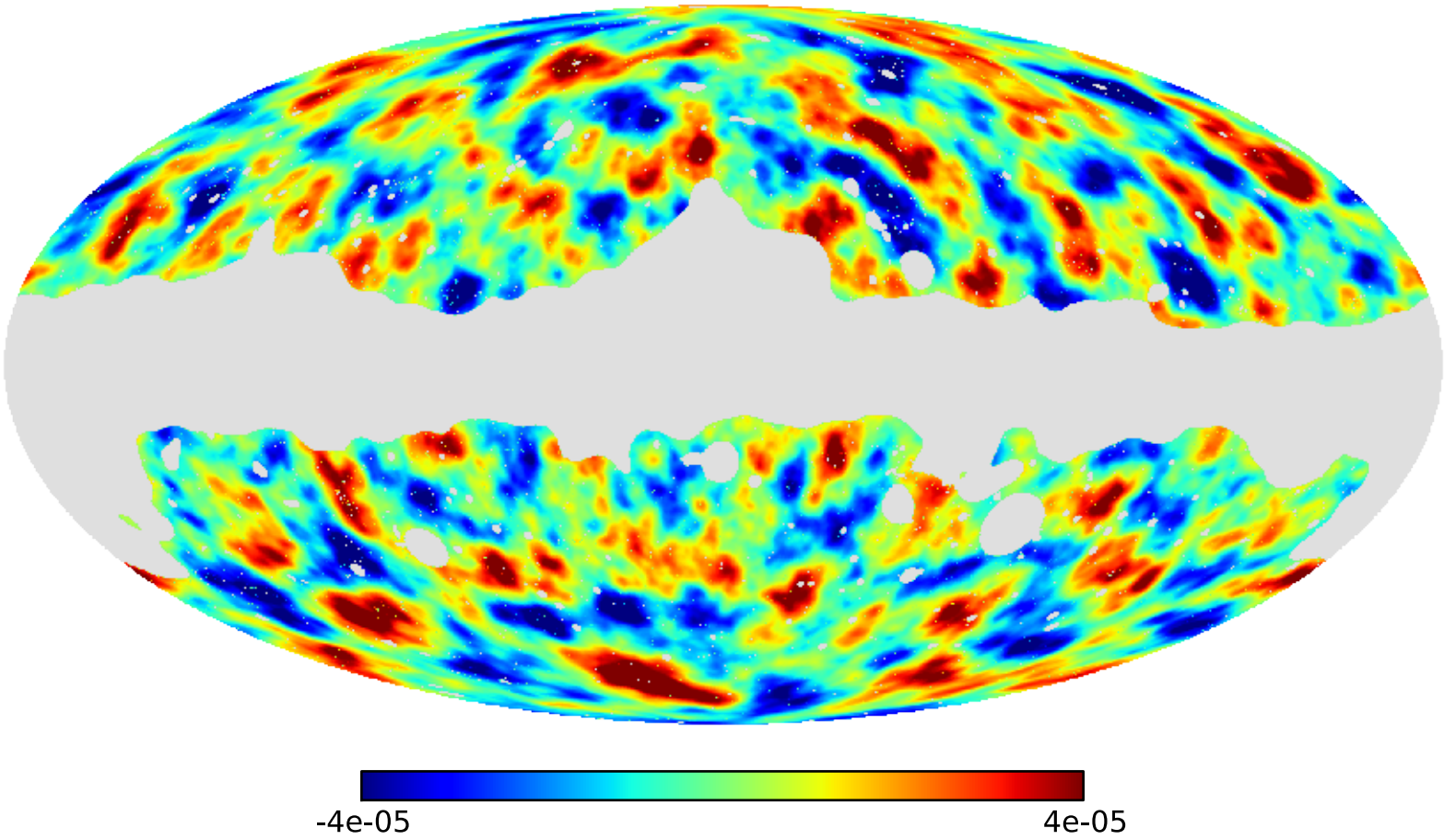
Reconstruction noise levels



Planck 2013 *TT*

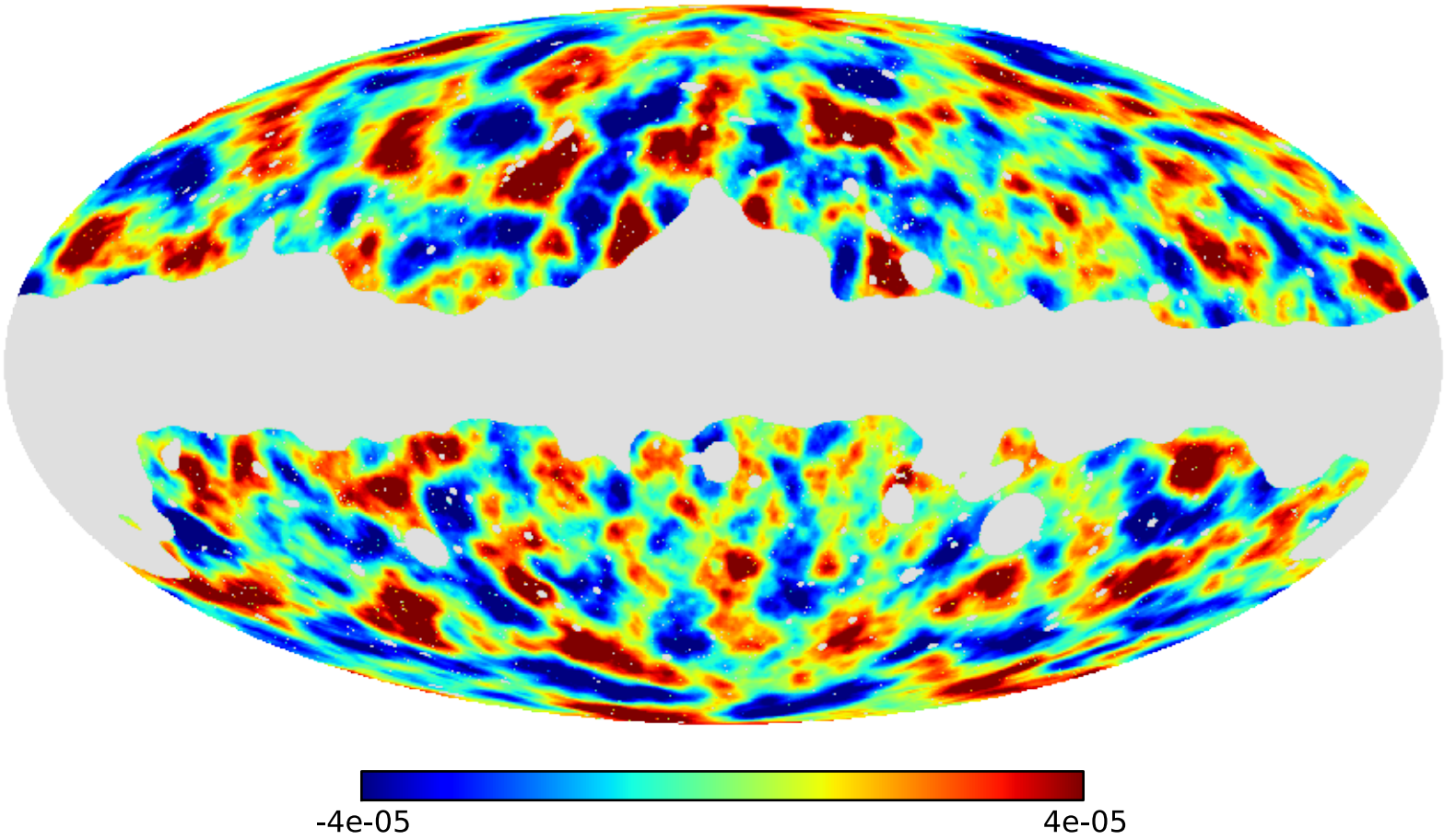


Planck 2014 *TT*



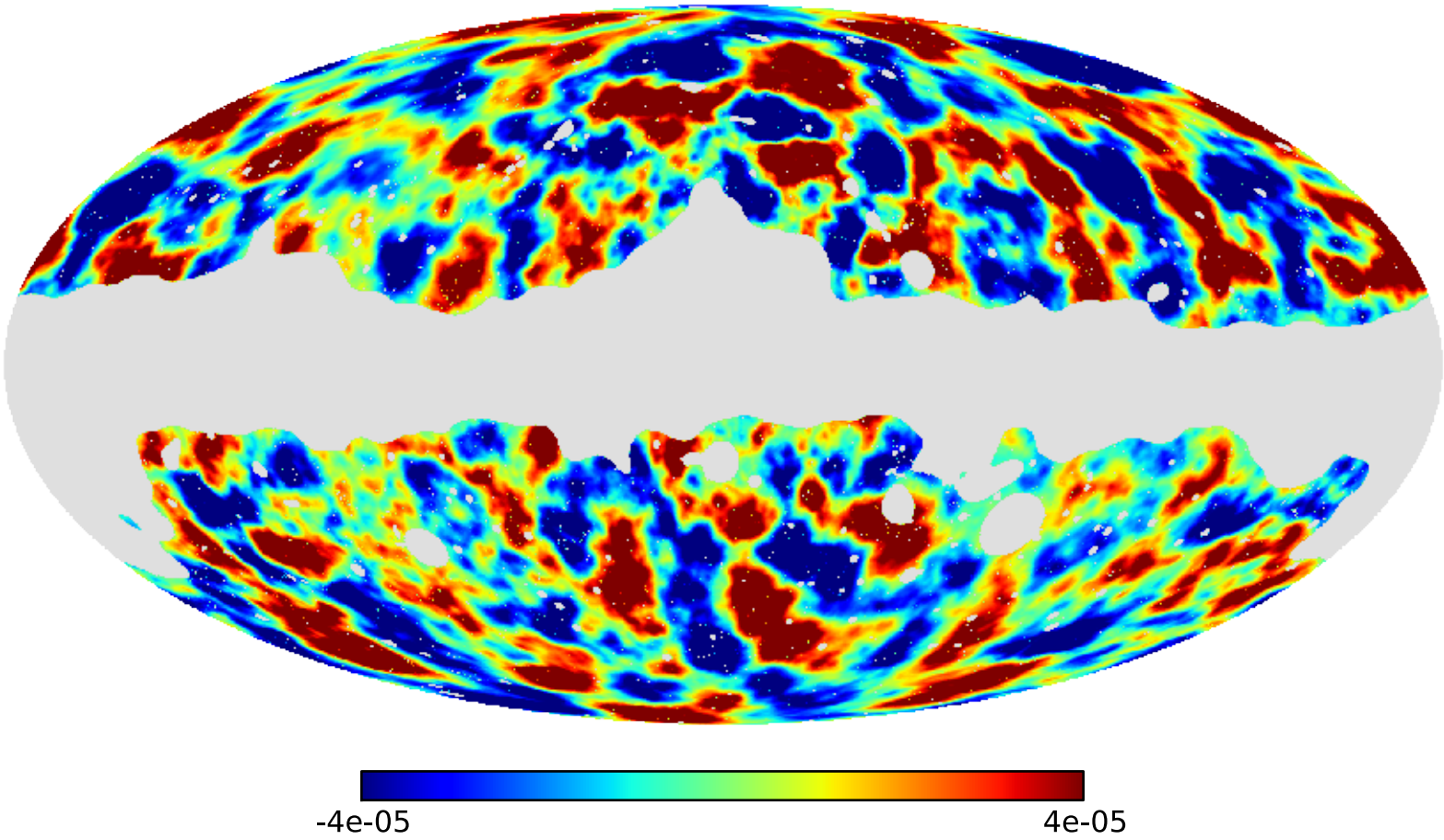
Preliminary

Planck 2014 *TE*



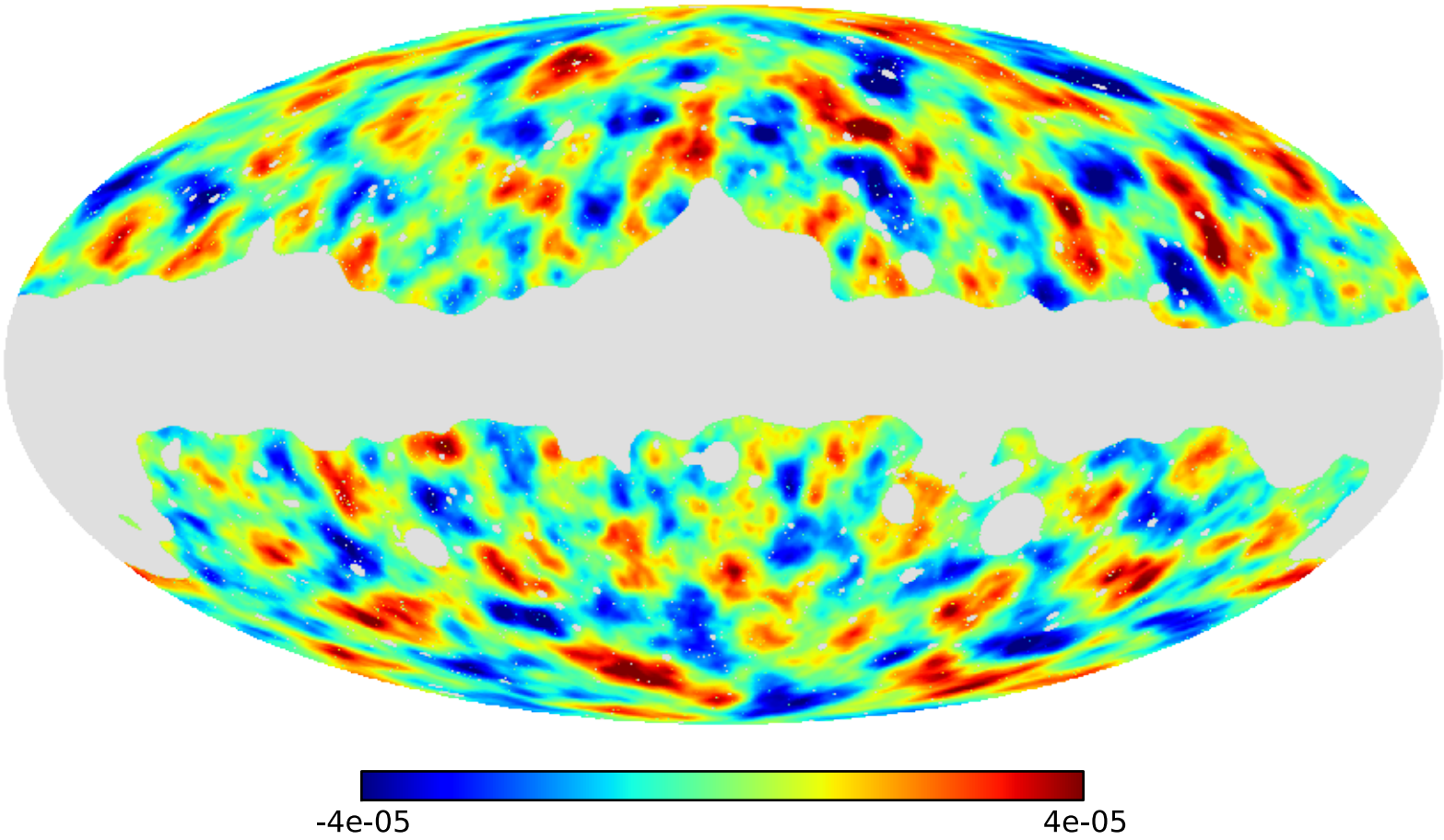
Preliminary

Planck 2014 *EE+BB*



Preliminary

Planck 2014 minimum-variance



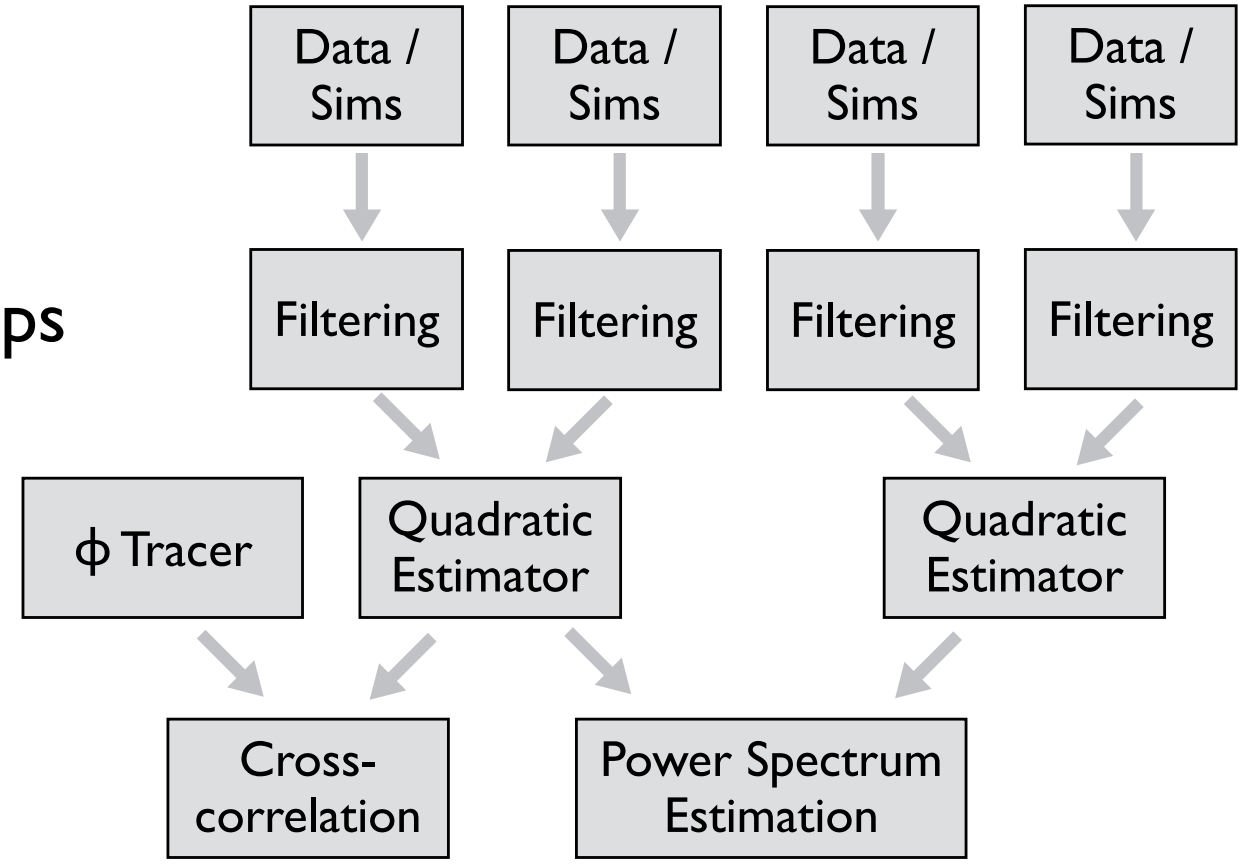
Preliminary

Lensing pipeline

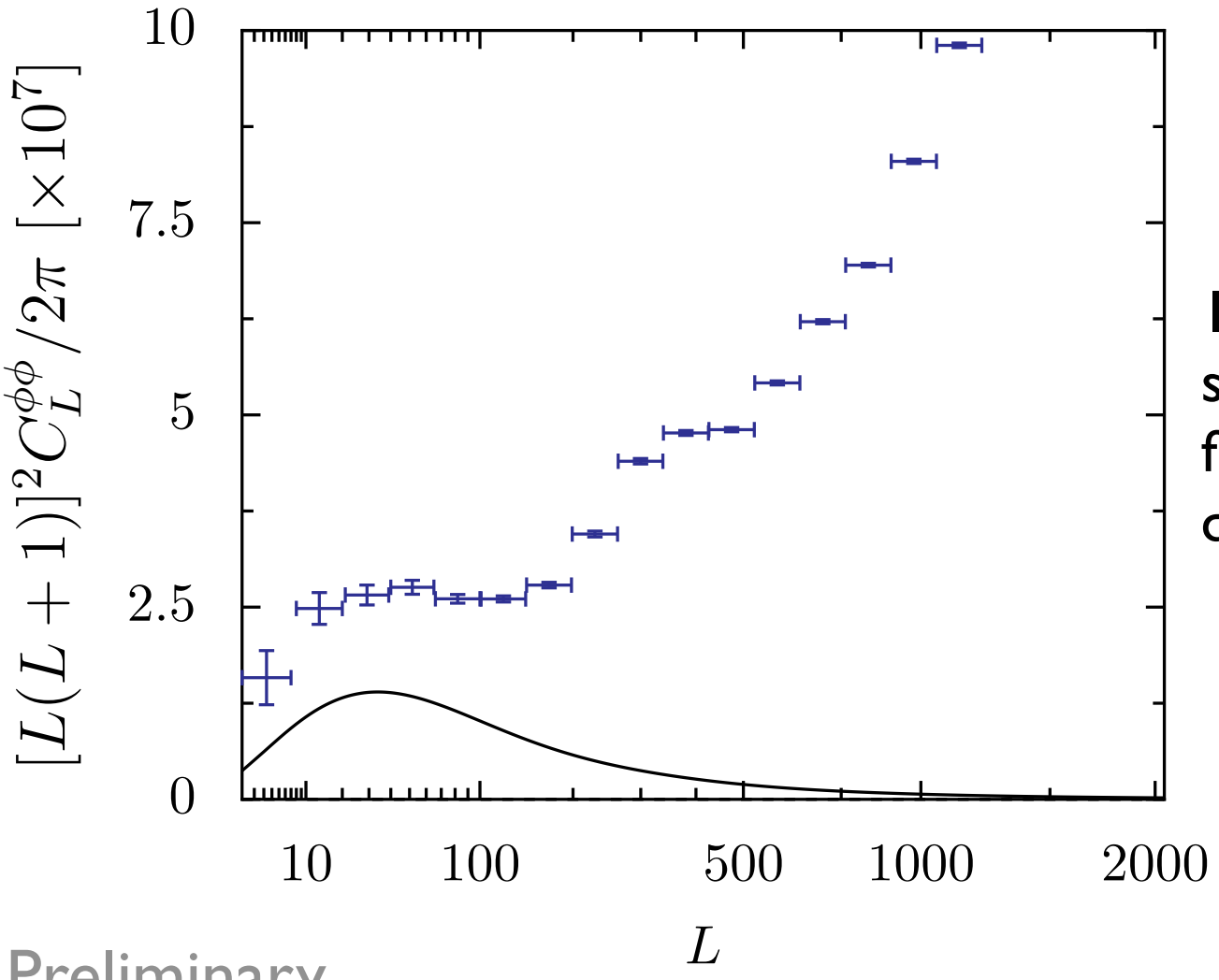
Process input maps

Estimate ϕ from off-diagonal 2-pt

Estimate ϕ power spectrum



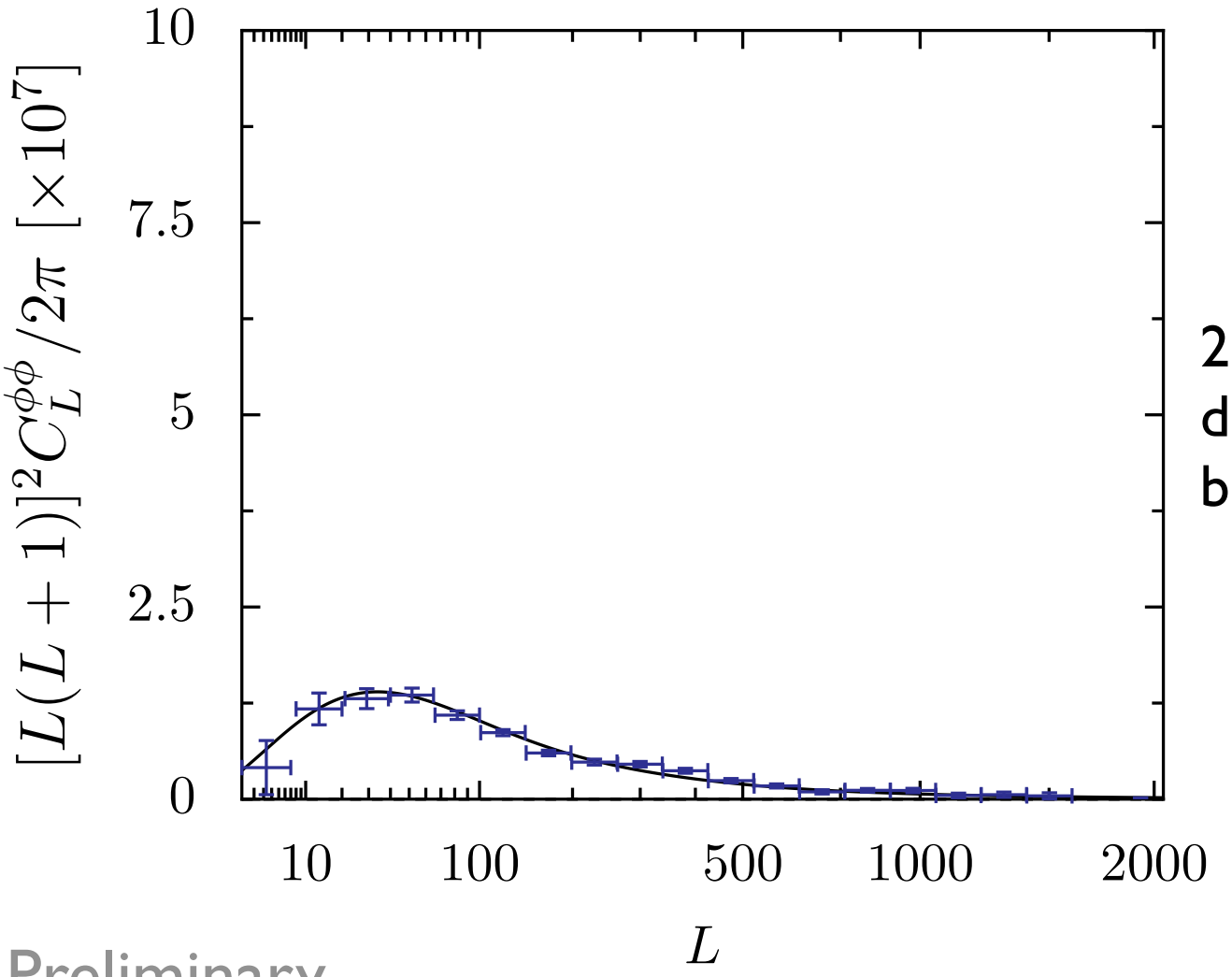
Power spectrum estimation



1. Raw power spectrum of (mean-field-corrected) quadratic estimates

Preliminary

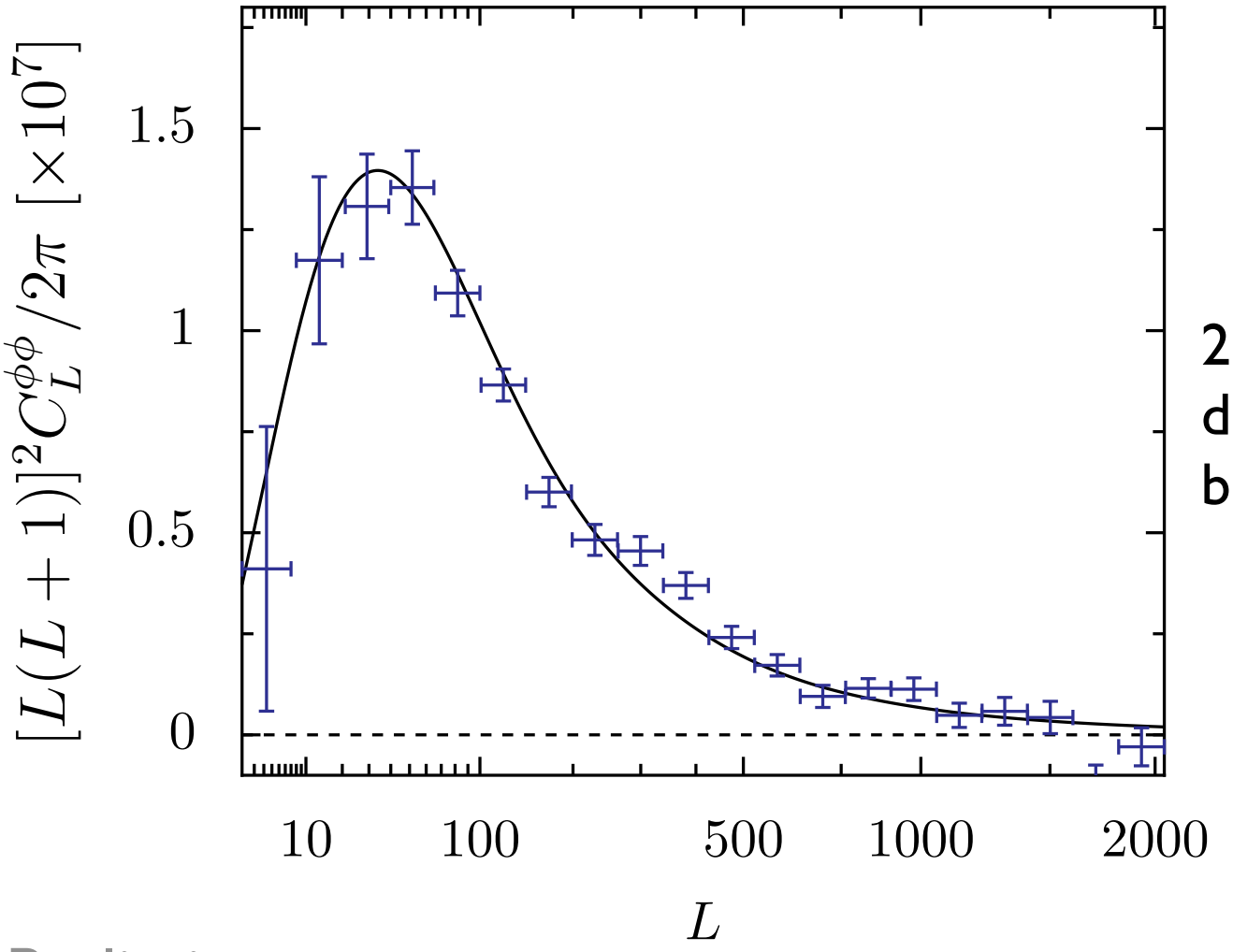
Power spectrum estimation



2. Subtract disconnected noise bias from sims

Preliminary

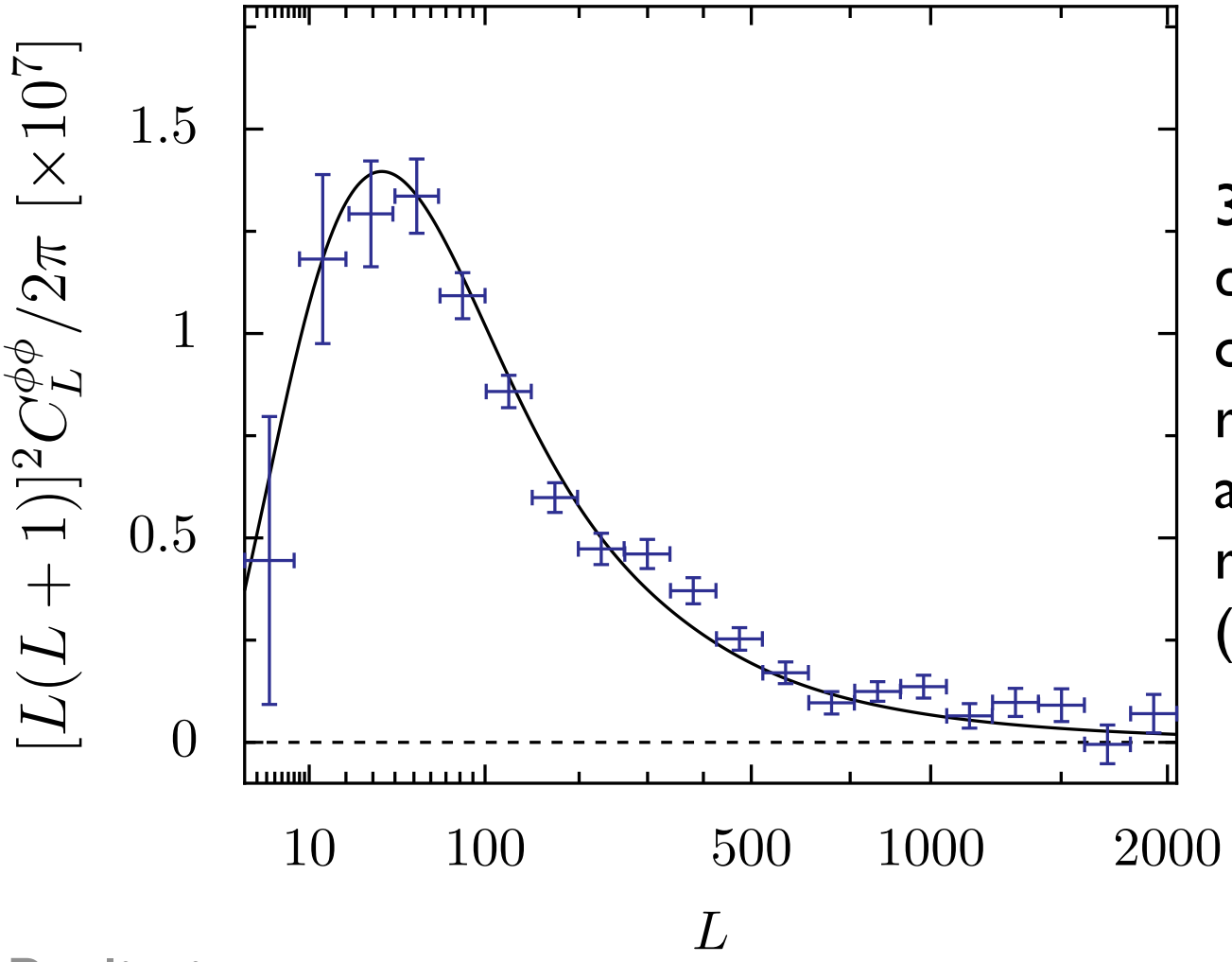
Power spectrum estimation



2. Subtract disconnected noise bias from sims

Preliminary

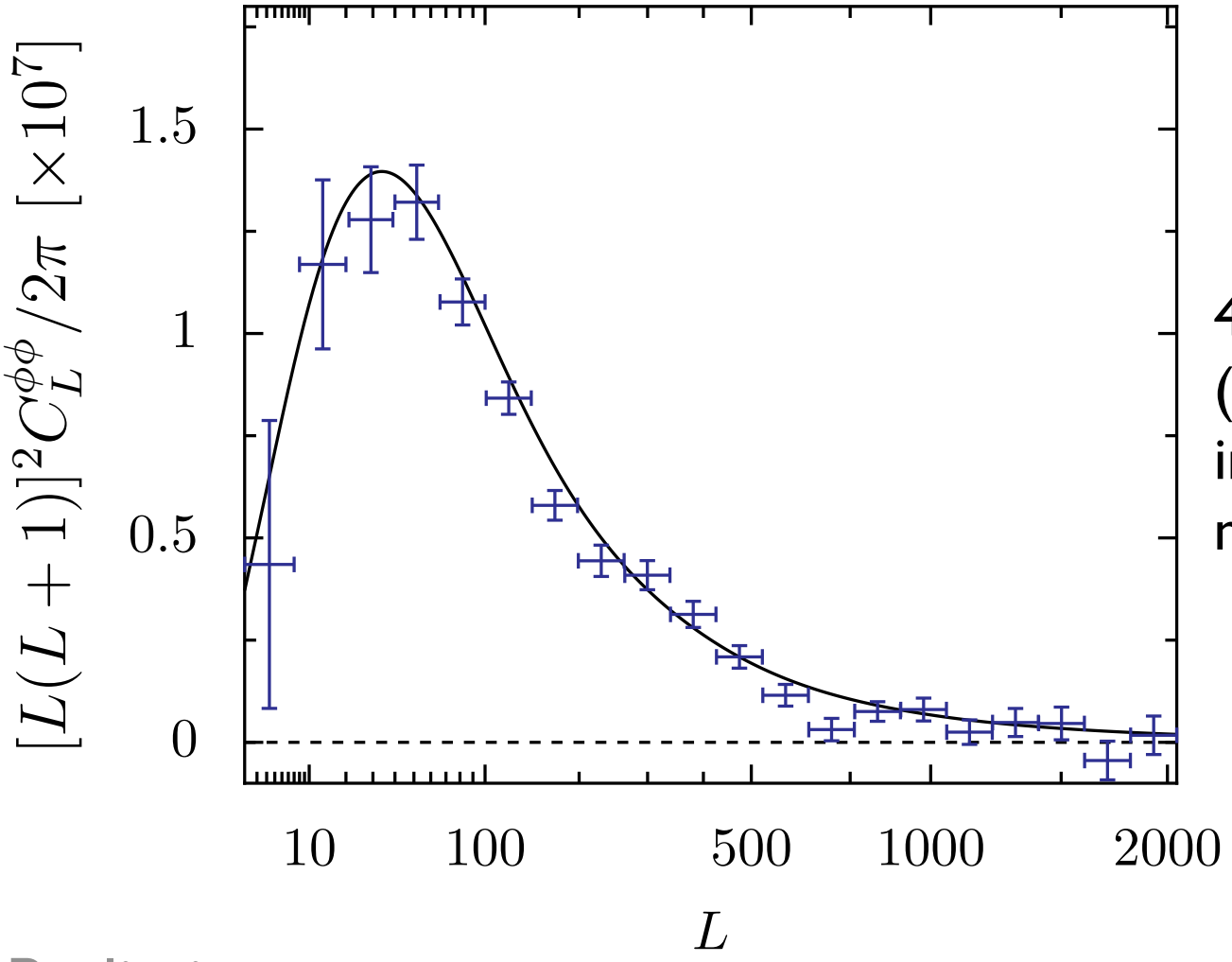
Power spectrum estimation



3. Subtract further data-based estimate of noise bias to reduce sensitivity to accuracy of sims, and reduce correlations (including with *TT*)

Preliminary

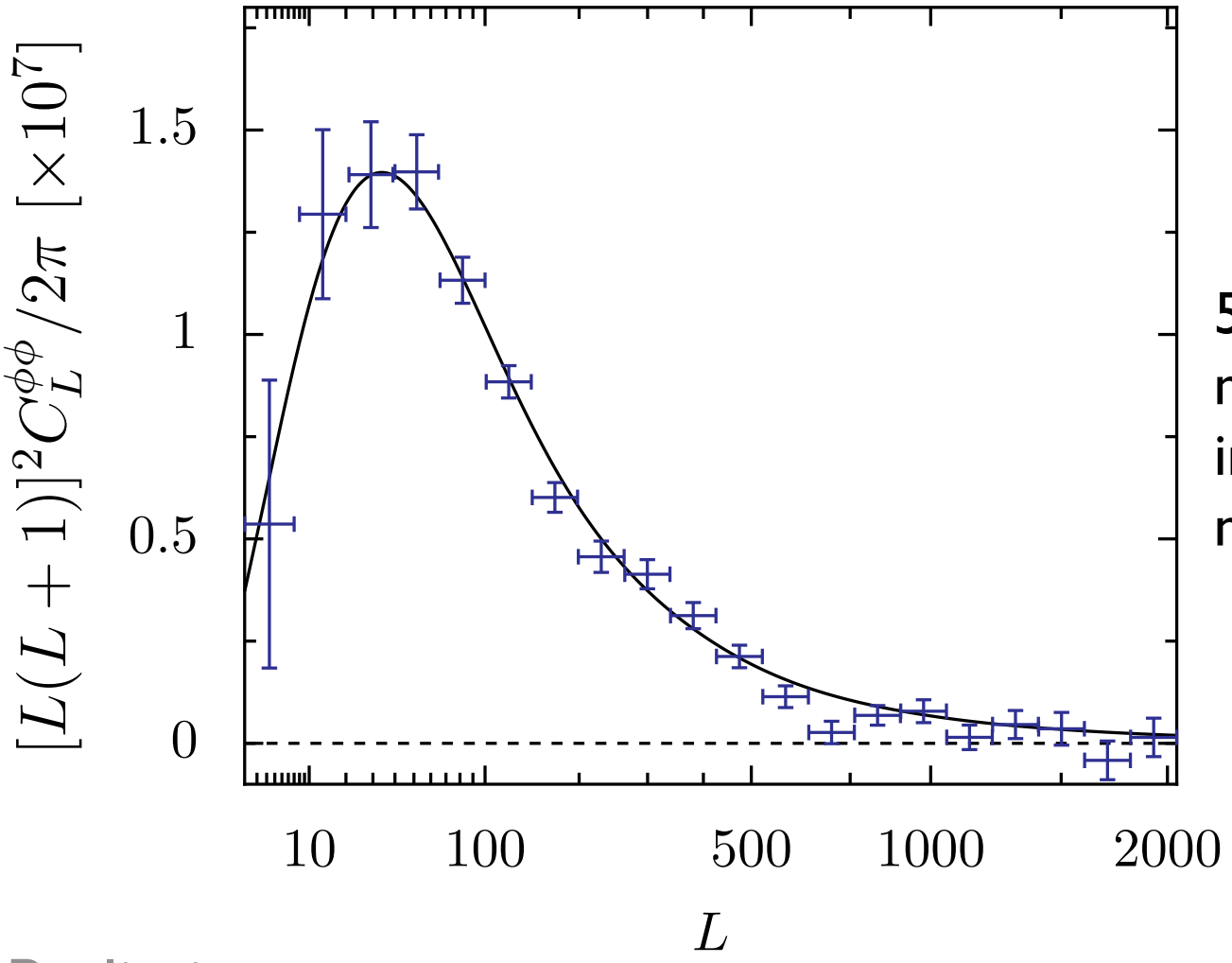
Power spectrum estimation



4. Subtract $N^{(1)}$ bias (further correction in likelihood for model dependence)

Preliminary

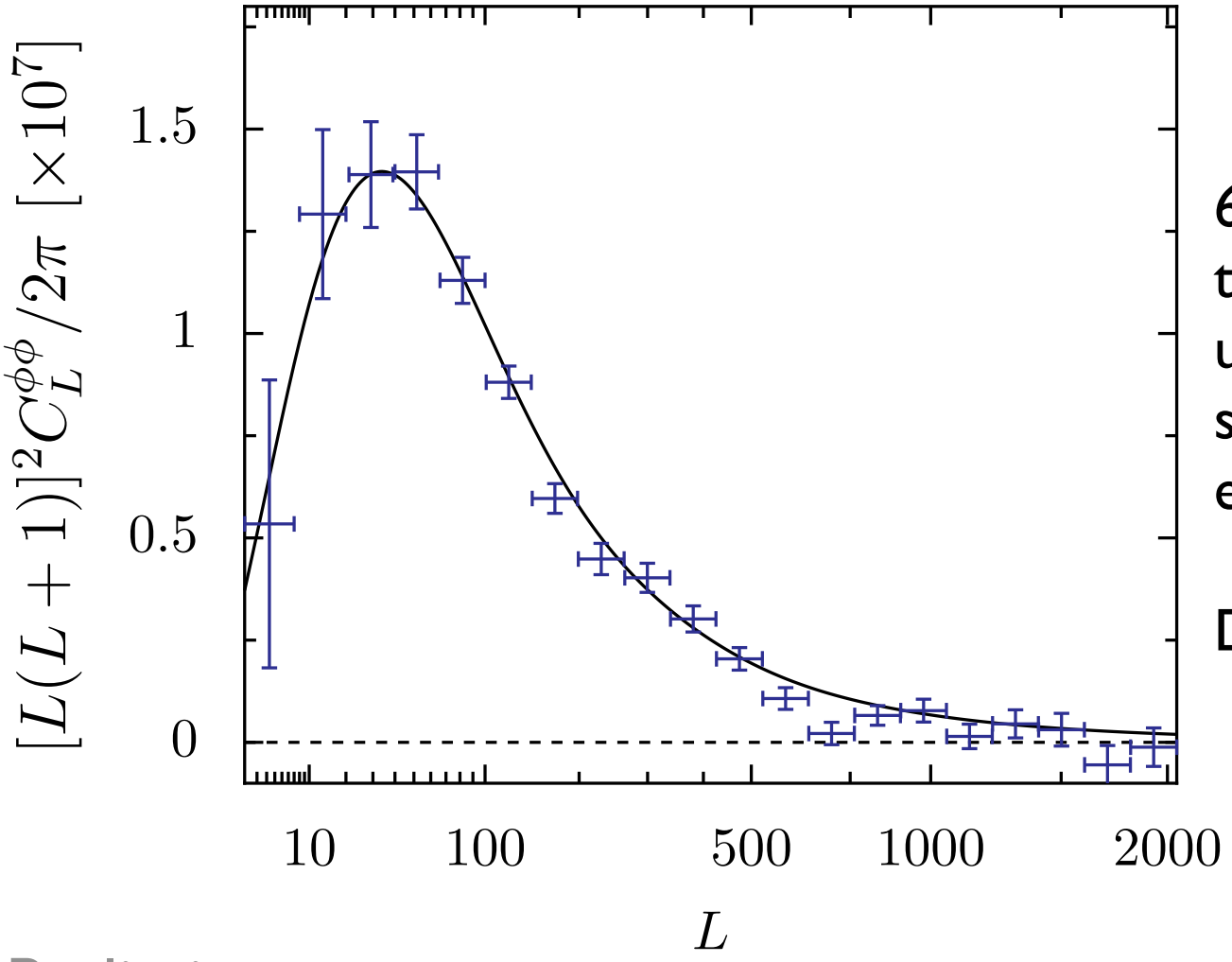
Power spectrum estimation



5. MC correction for mode-coupling and inaccuracies in normalisation

Preliminary

Power spectrum estimation

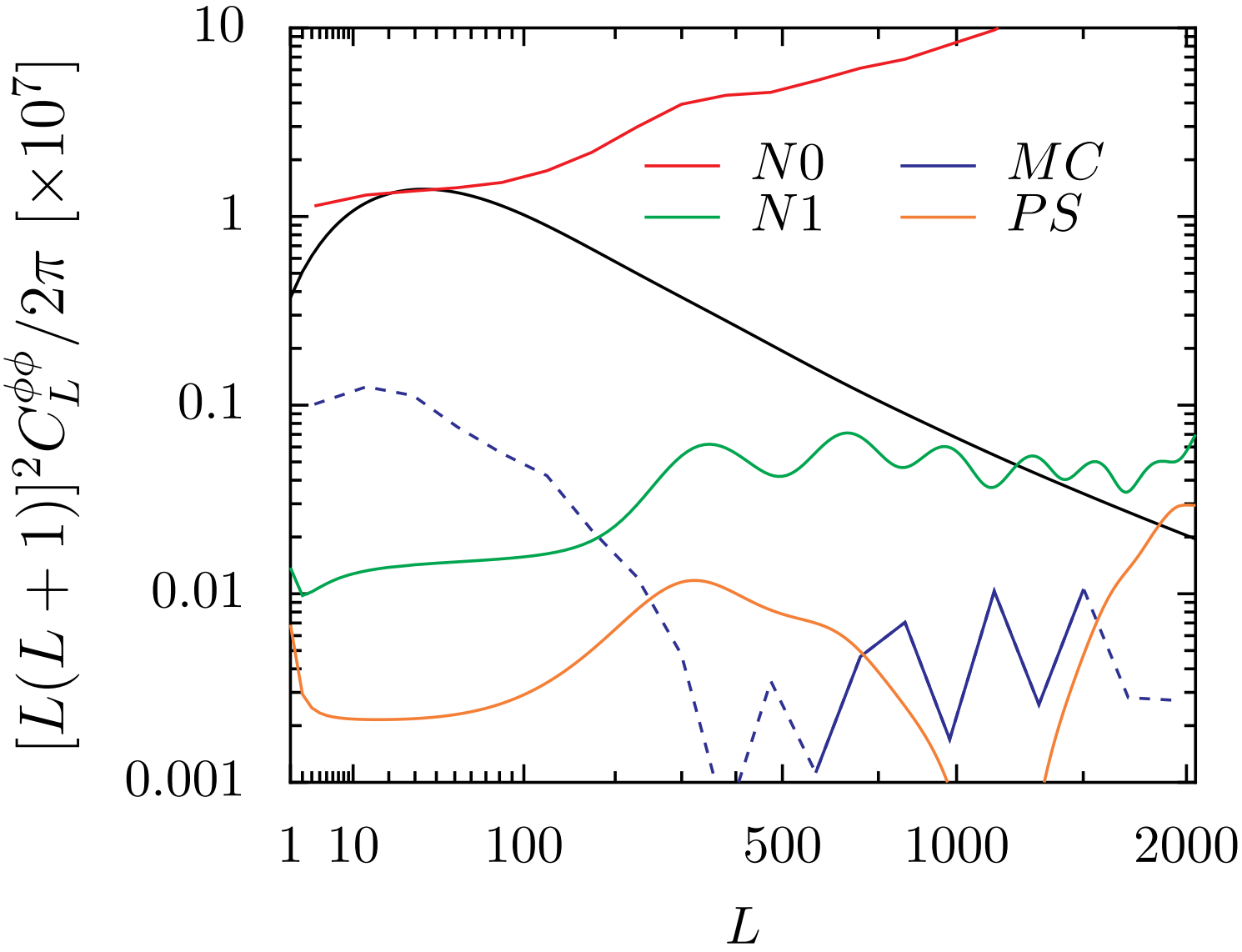


6. Correct for trispectrum of unresolved point sources (amplitude estimated from data)

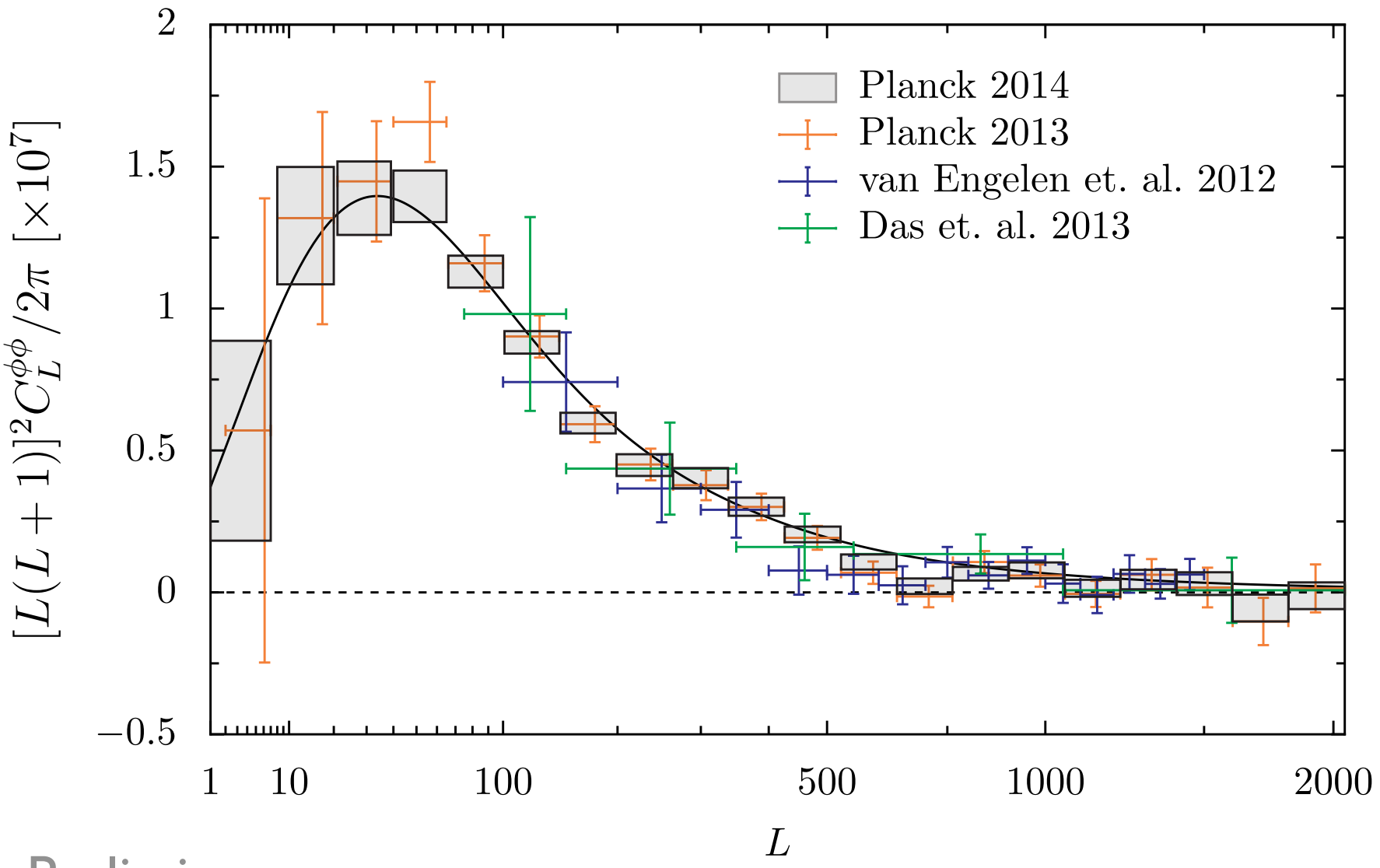
Done!

Preliminary

Power spectrum biases

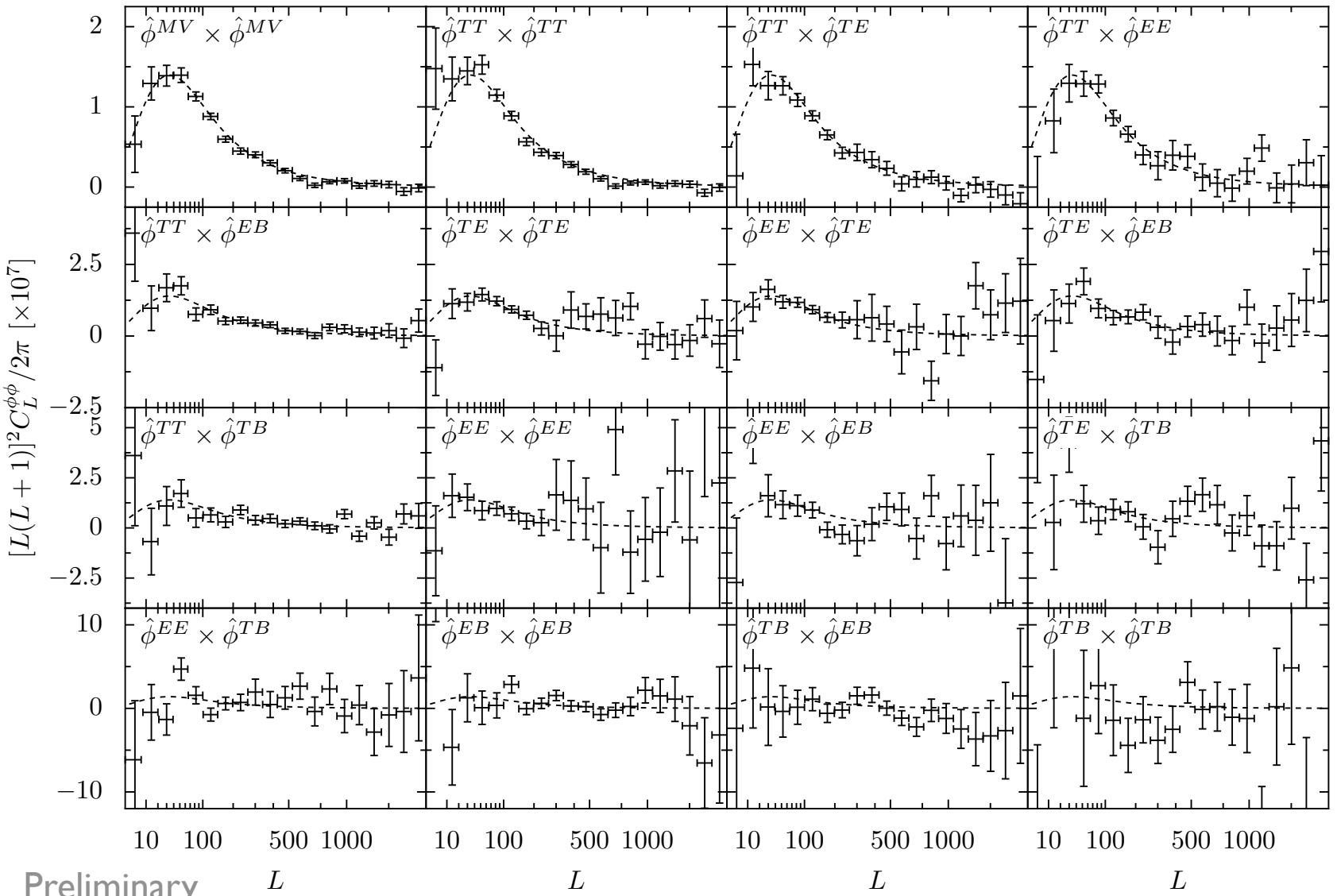


2014 MV power spectrum



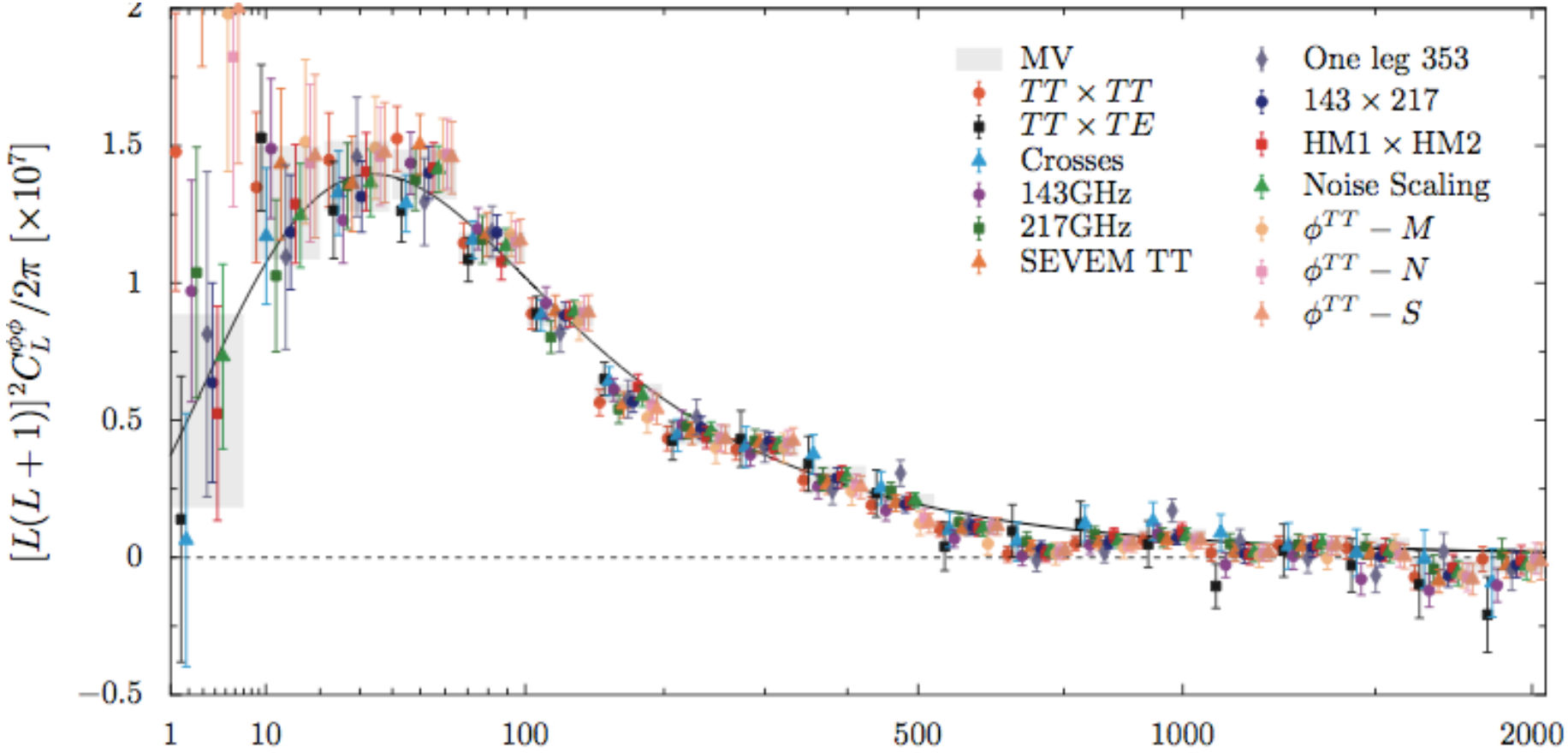
Preliminary

15 individual cross-spectra



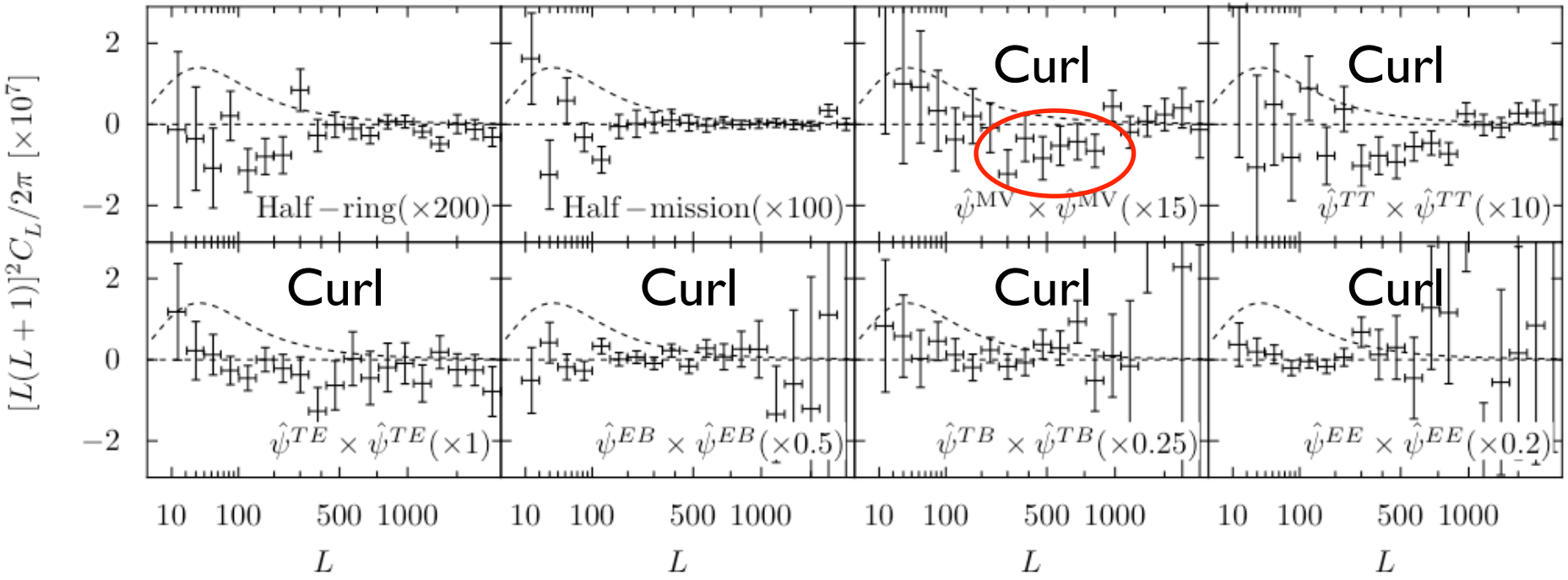
Preliminary

Internal consistency tests



Preliminary

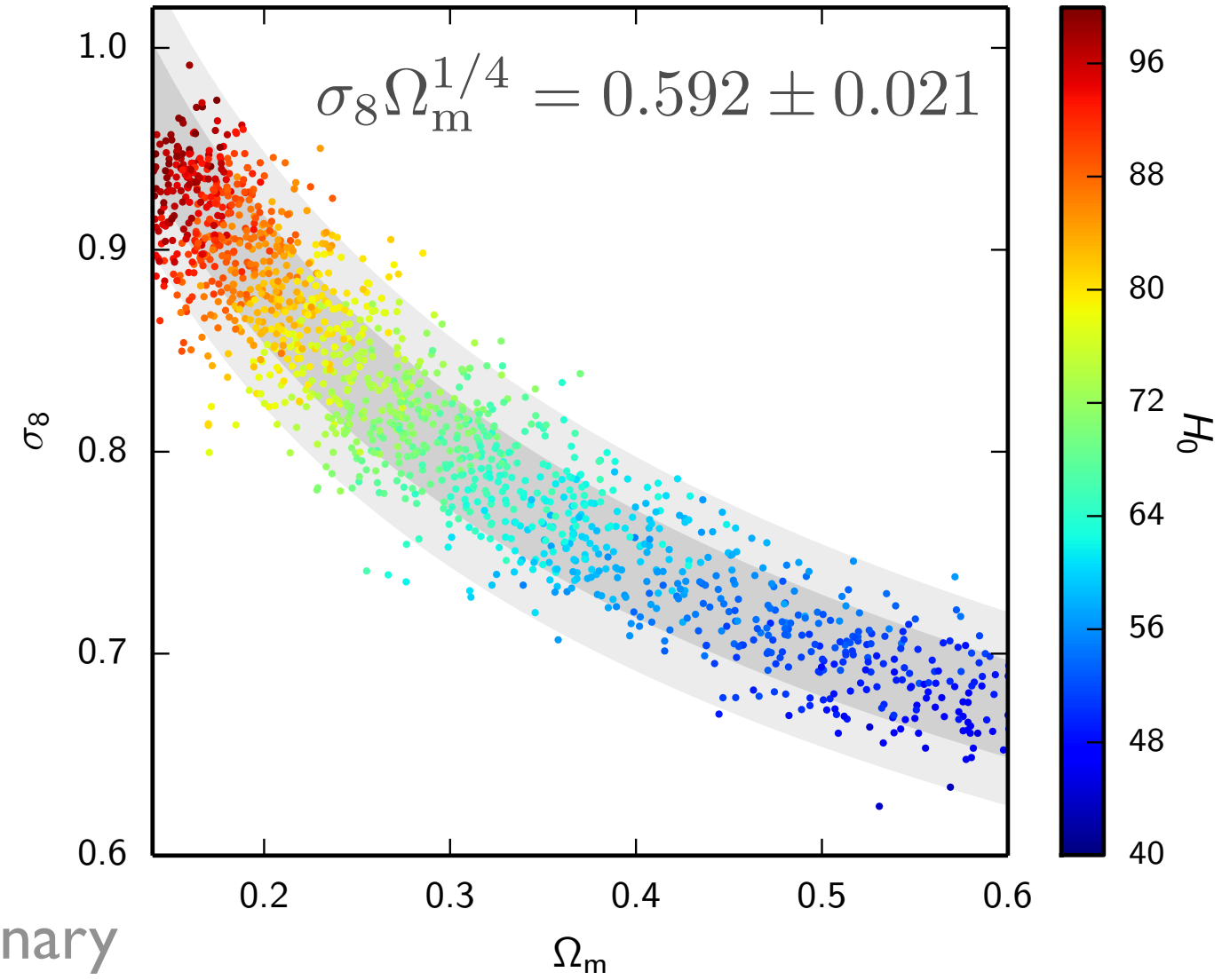
Null tests



"Conservative" likelihood uses $40 \leq L \leq 400$

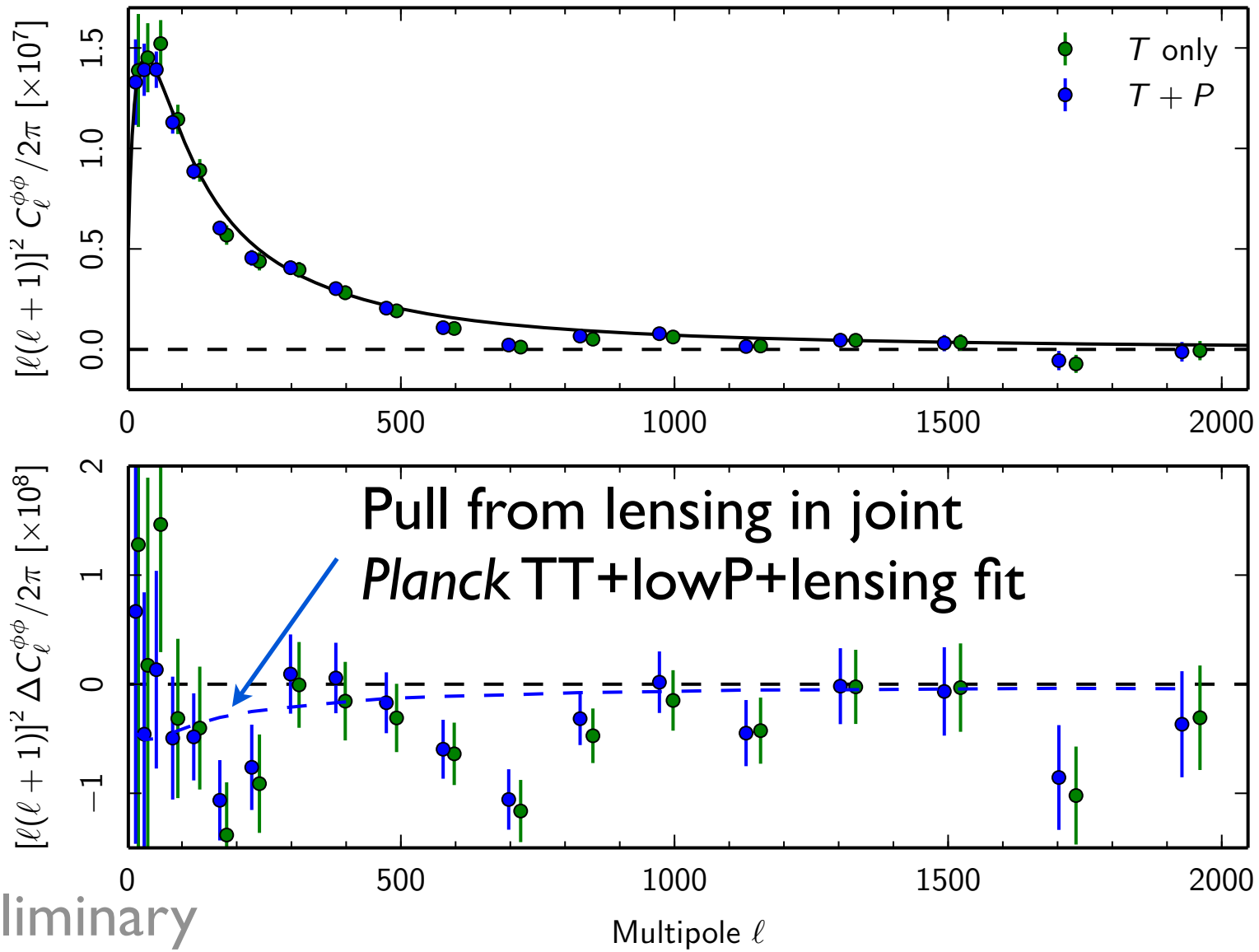
Preliminary

LCDM "lens-only" constraints



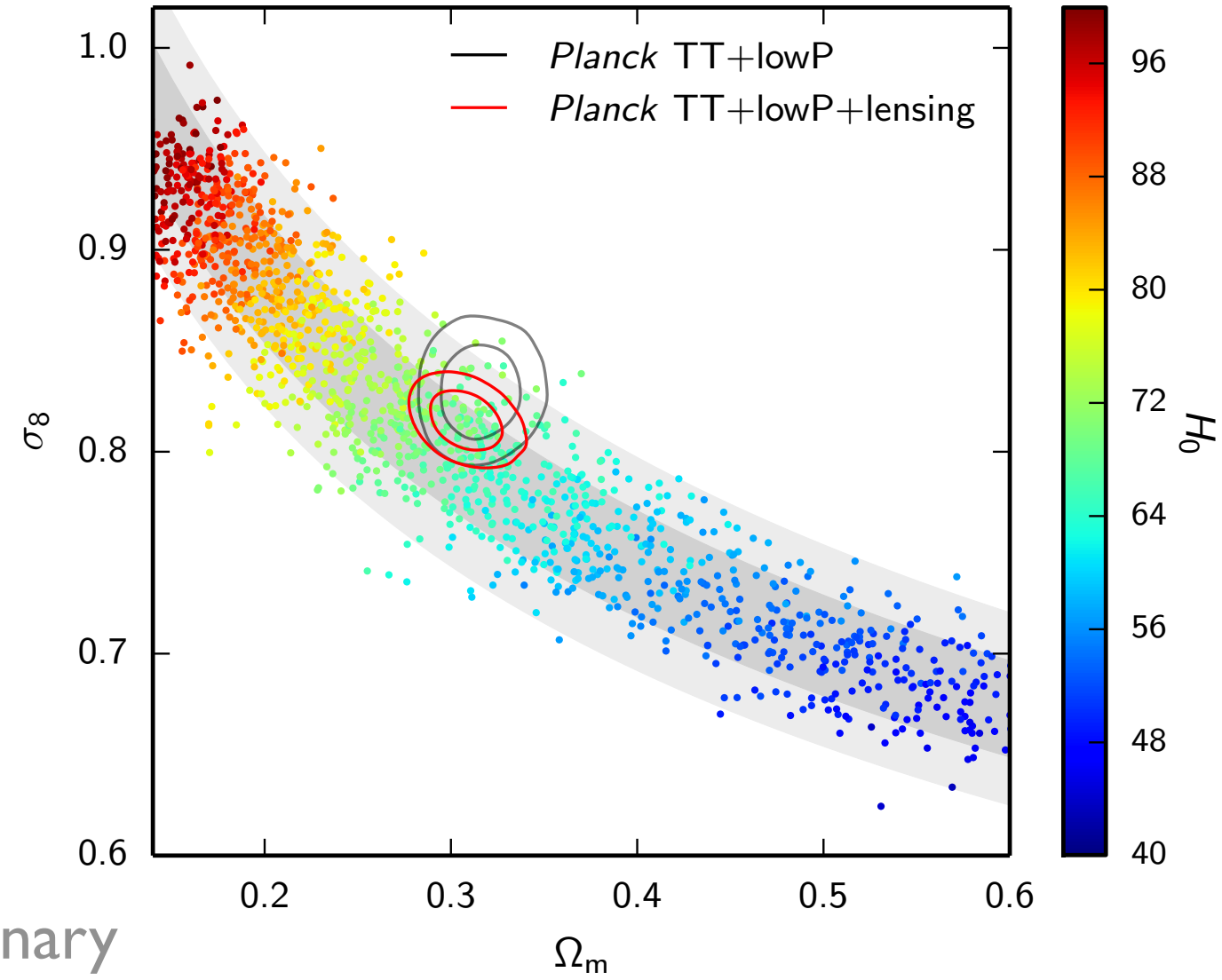
Preliminary

LCDM consistency with *TT*



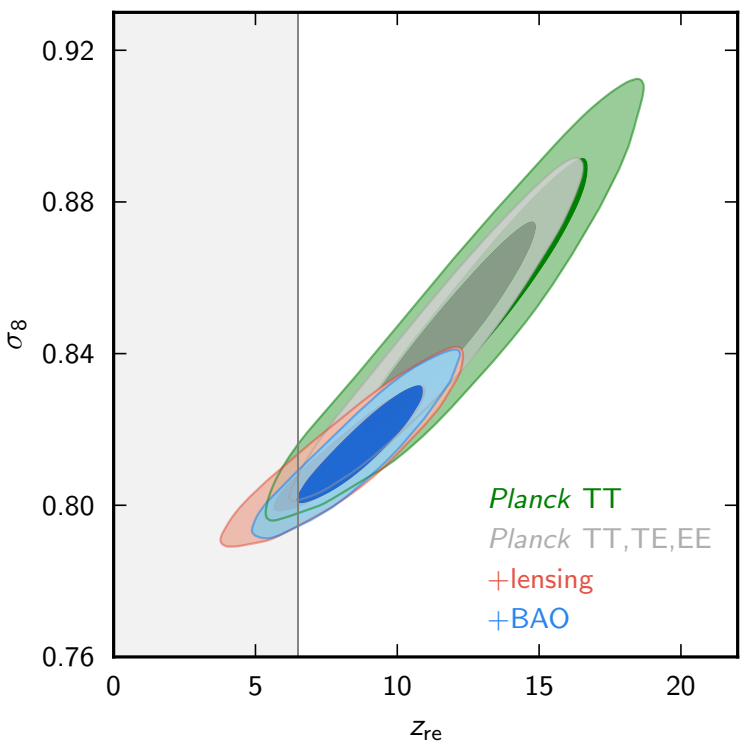
Preliminary

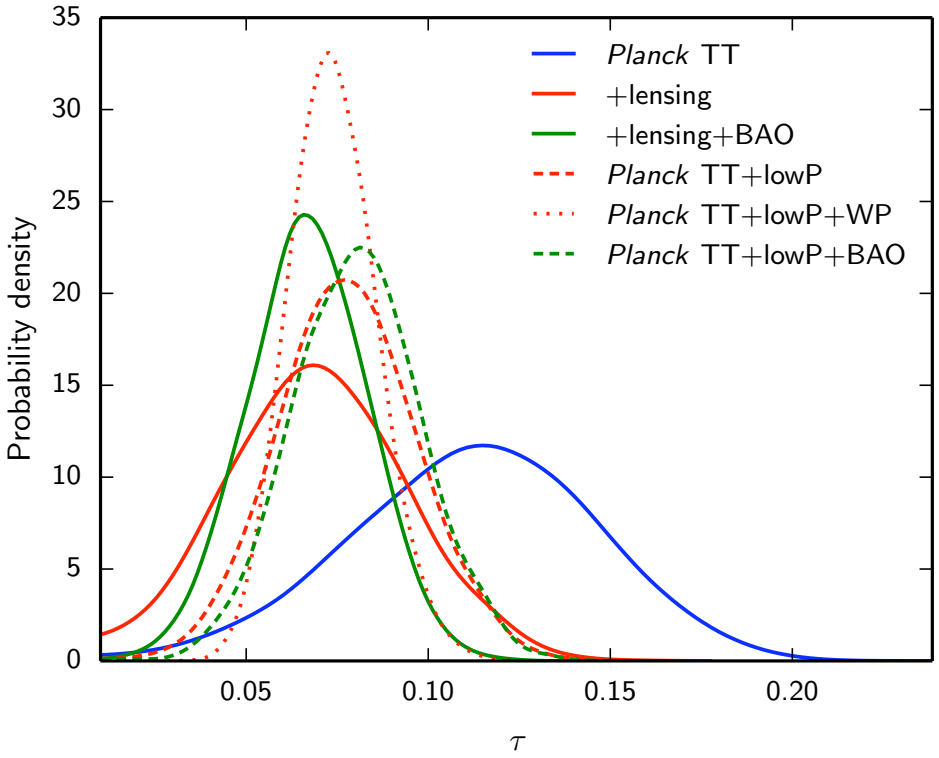
LCDM joint constraints



Preliminary

Reionization

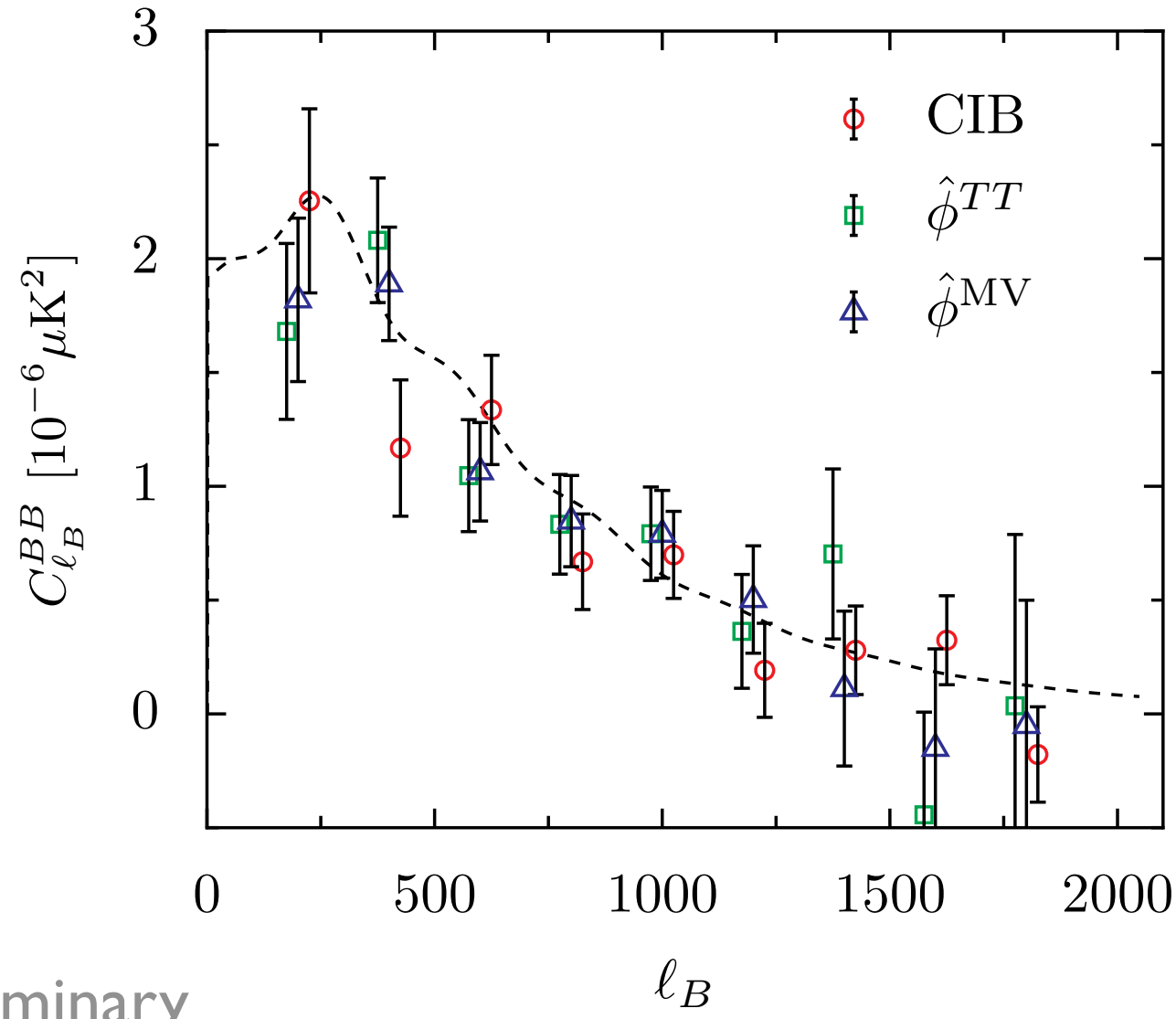




Consistent picture from *TT*+lensing or low-*l* polarization

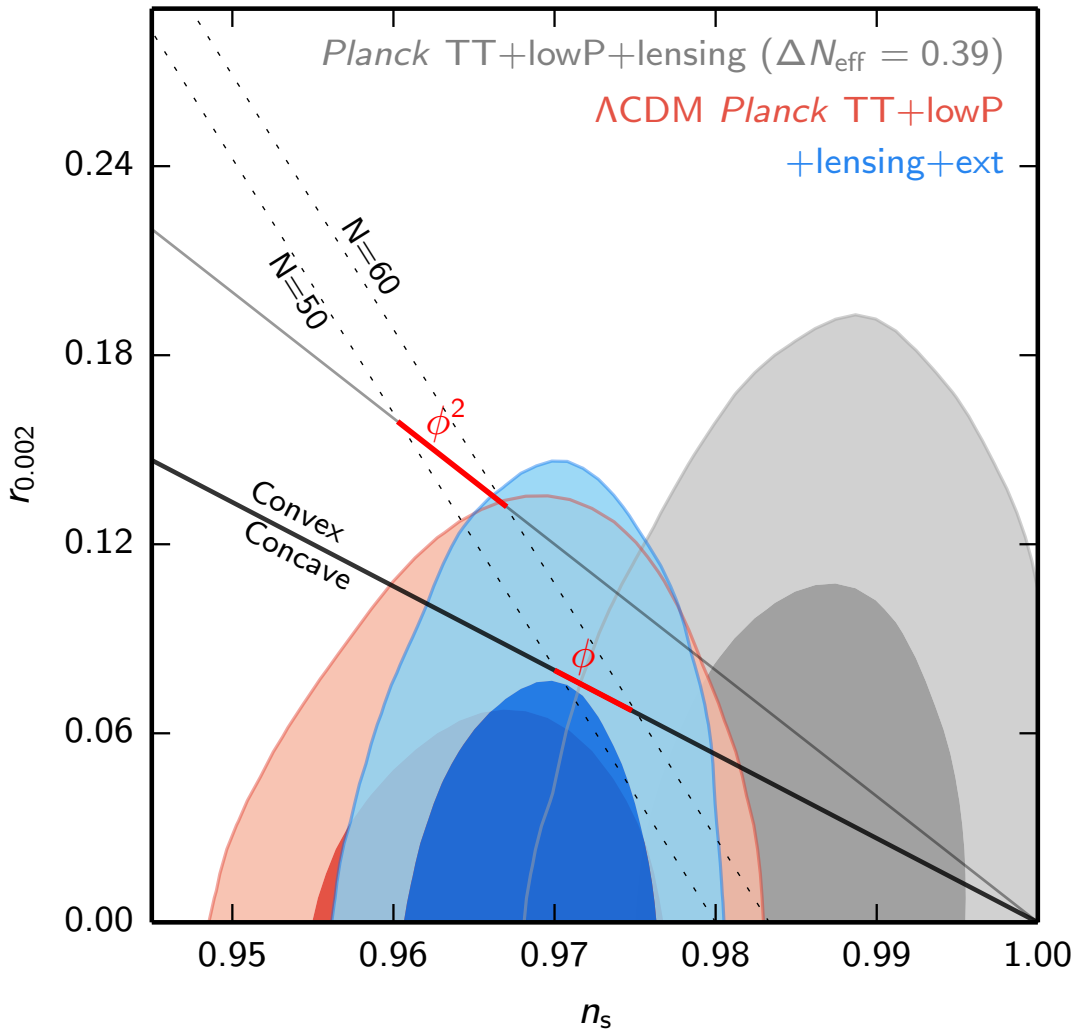
Preliminary

B-mode power (indirect)



Preliminary

Constraints on inflation



$$Planck\ \mathrm{TT{+}lowP}:$$

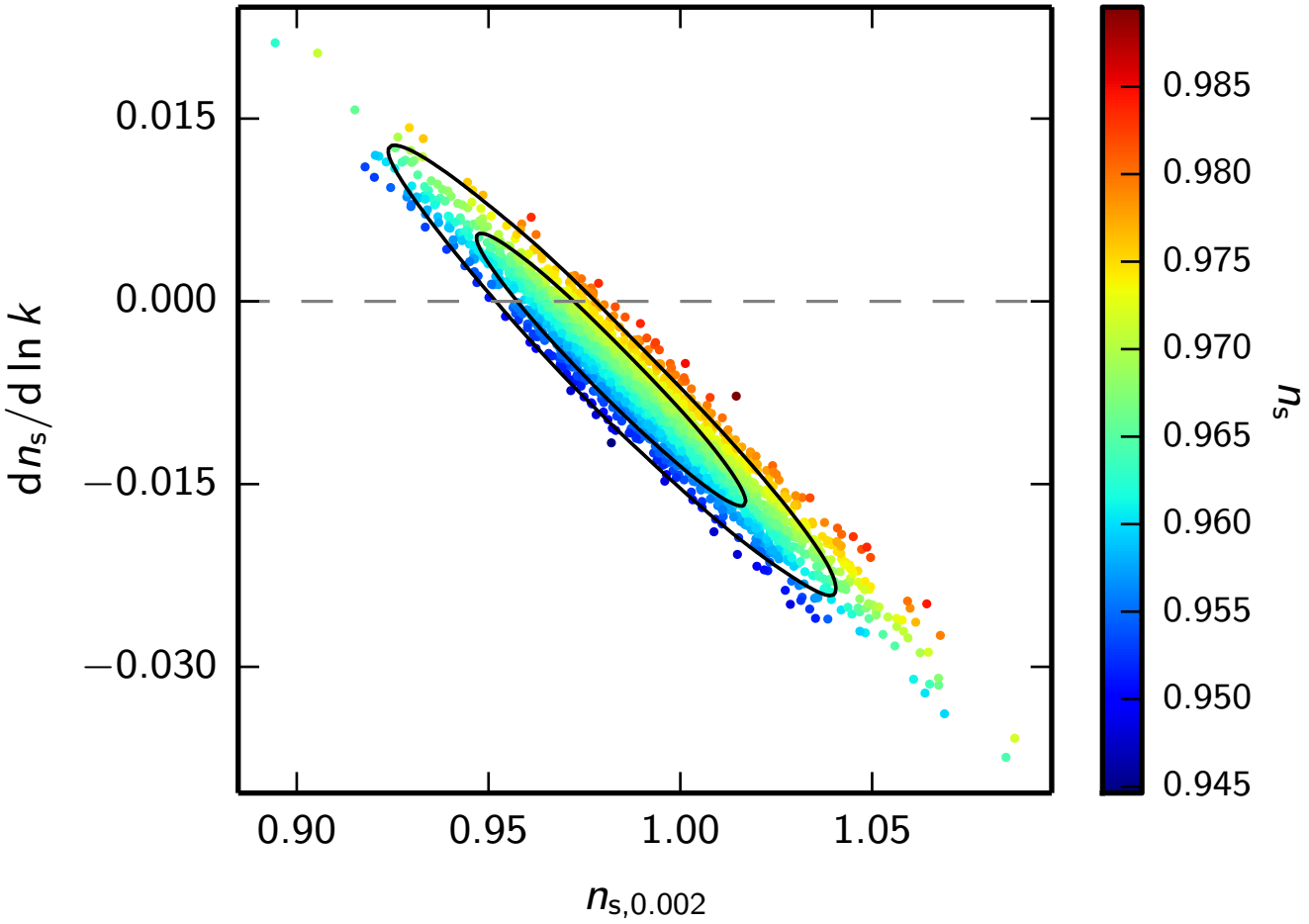
$$n_{\rm s} = 0.9666 \pm 0.0062$$

$$r_{0.002} < 0.11\ (95\%)$$

Model-dependent and C.V. limited from *TT* → *BB* measurements

Preliminary

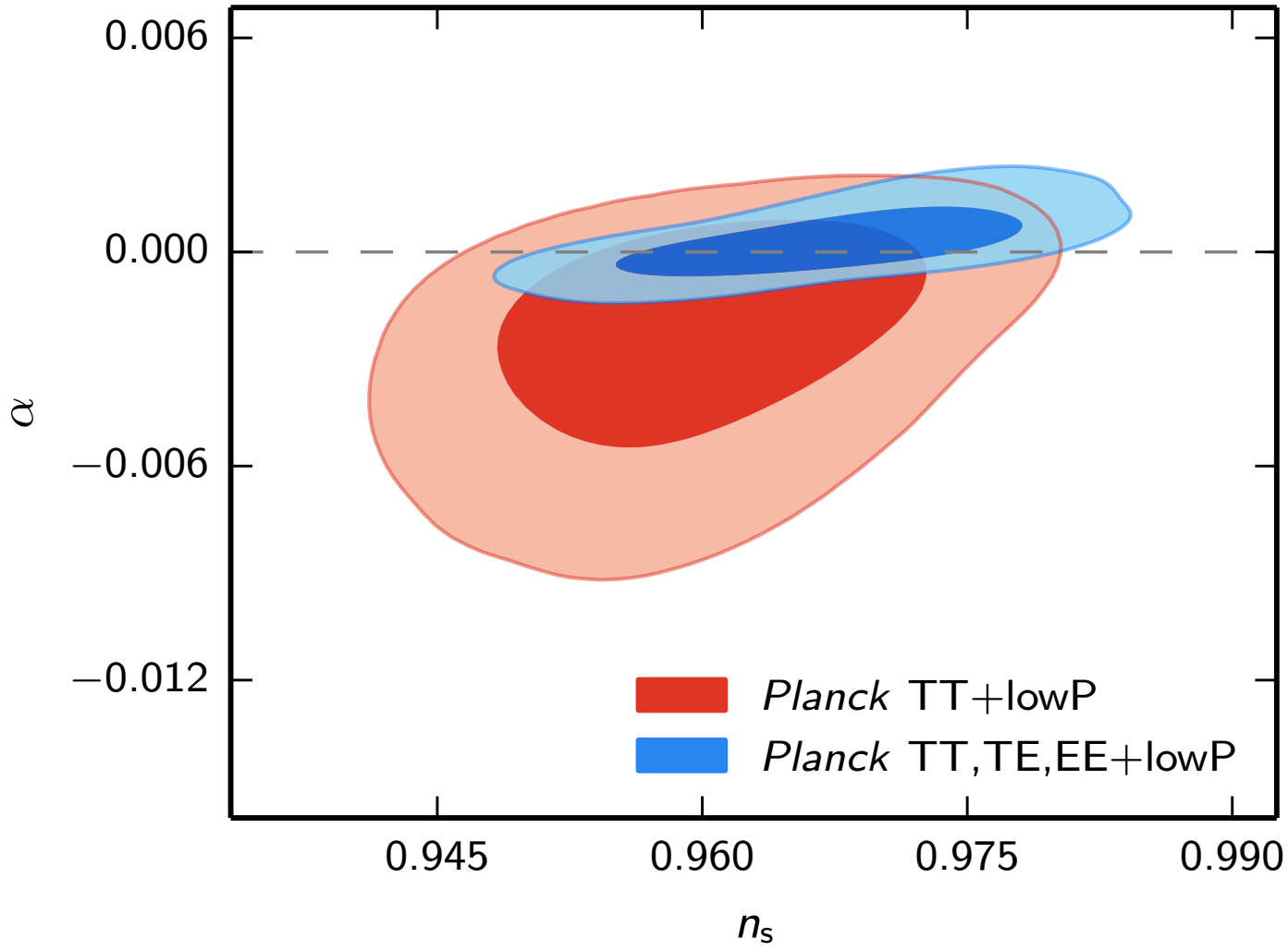
No strong evidence for running



$$dn_s/d\ln k = -0.0084 \pm 0.0082 \quad (Planck\ \mathrm{TT{+}lowP};\ 68\%)$$

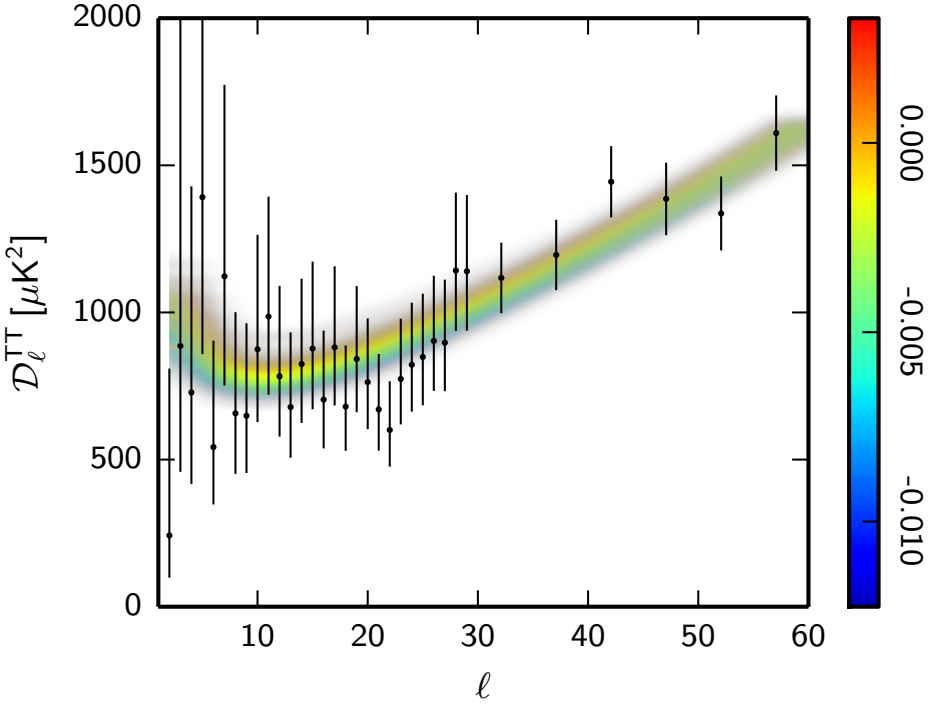
Preliminary

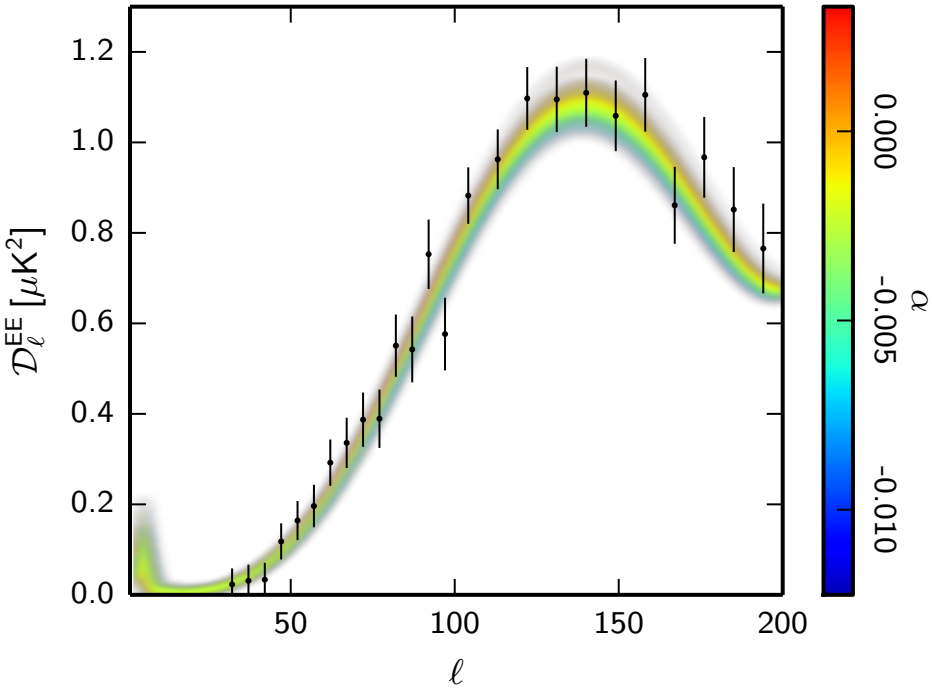
Adiabatic fluctuations



Preliminary

What drives this?

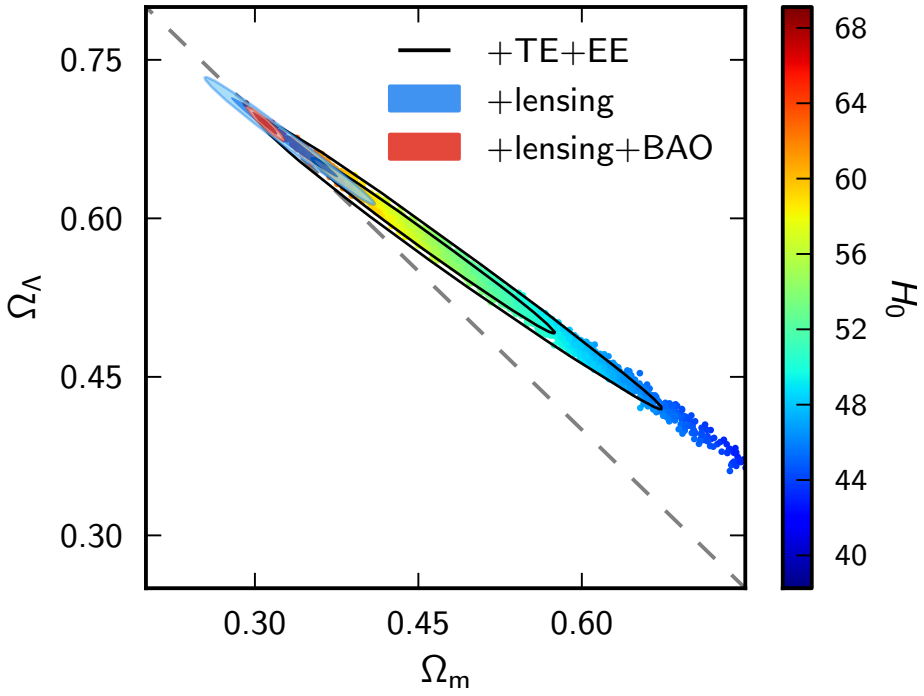


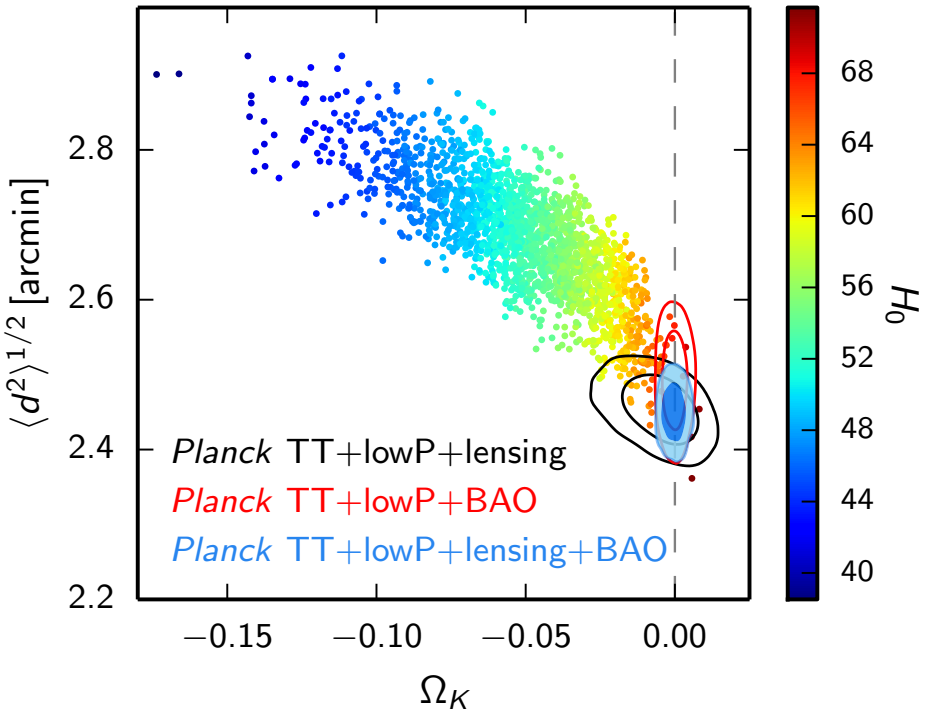


Preference for anti-correlated isocurvature from low-*l TT* disfavoured around first peak in *EE*

Preliminary

Curvature





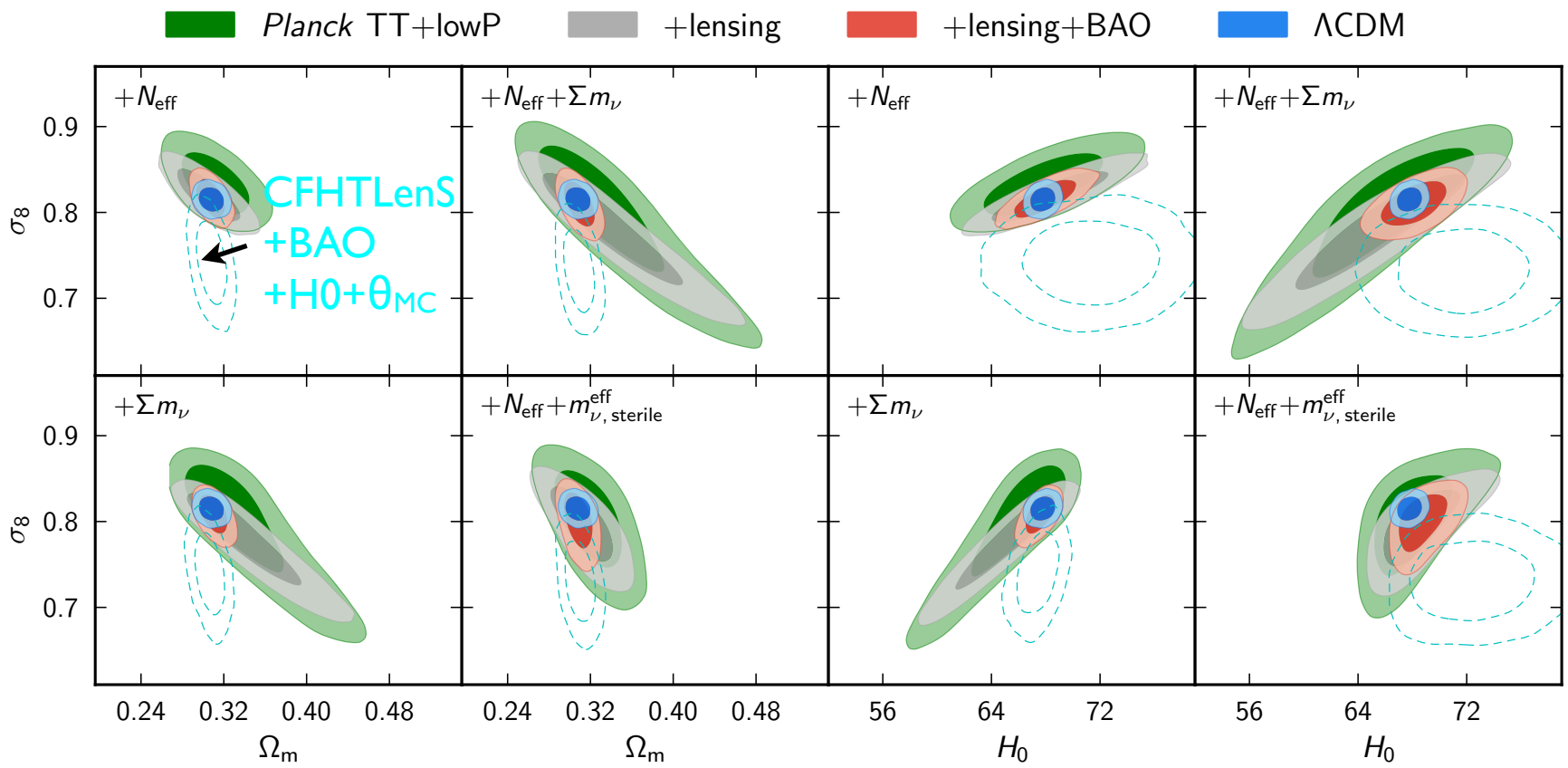
$$\Omega_K = -0.052^{+0.032}_{-0.018} \quad (68\%;\ \textit{Planck}\ \mathrm{TT{+}lowP})$$

$$\Omega_K = -0.0053^{+0.0089}_{-0.0075} \quad (68\%;\ \textit{Planck}\ \mathrm{TT{+}lowP{+}lensing})$$

$$\Omega_K = -0.0002 \pm 0.0026 \quad (68\%;\ \textit{Planck}\ \mathrm{TT{+}lowP{+}lensing{+}BAO})$$

Preliminary

Tensions revisited



Massive sterile neutrinos do little to ease tension with cosmic shear

Preliminary


esa
planck
cnes
agenzia spaziale italiana
NASA
cnrs
DTU Space
National Space Institute
Science & Technology Facilities Council
INAF
ISTITUTO NAZIONALE DI ASTROFISICA
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
PLANCK
LFI
HFI
PLANCK
a look back to the birth of Universe
National Research Council of Italy
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
IAS
orsay
IAP
INAF - IASF BO
ISTITUTO NAZIONALE DI ASTROFISICA
ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA
CSA ASC
DLR
Deutsches Zentrum
für Luft- und Raumfahrt e.V.
UK SPACE
AGENCY
MAX-PLANCK-GESELLSCHAFT
Aalto University
ioa
KICC
CAVENDISH ASTROPHYSICS
UNIVERSITY OF CAMBRIDGE
CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD
irfu
cea
saclay
CEFCA
irap
CITA–ICAT
IASF
cnrs
INSU
Observer & comprendre
cnrs
IN2P3
Les deux infinis
BERKELEY LAB
ipac
HELSINKI INSTITUTE OF PHYSICS
IFCA
Instituto de Física de Cantabria
Imperial College London
UNIVERSITÀ DEGLI STUDI DI MILANO
NÉEL institut
IPAG
ISDC
DATA CENTRE FOR ASTROPHYSICS
JPL
LAL
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE
l'Observatoire de Paris
LERMA
LPSC
Grenoble
NERSC
MANCHESTER 1824
The University of Manchester
MilliLab
Science & Technology Facilities Council
Rutherford Appleton Laboratory
Max-Planck-Institut für Astrophysik
NUI MAYNOOTH
INAF
OSSERVATORIO ASTRONOMICO DI PADOVA
SAPIENZA
UNIVERSITÀ DI ROMA
UBC
UC
UNIVERSIDAD DE CANTABRIA
UCSB
SISSA
ALMA
ESO
US
University of Sussex
HAVERFORD
esa
UNIVERSITY OF HELSINKI
UNIVERSITÉ DE GENÈVE
UNIVERSITY OF TORONTO
UNIVERSITÉ DE PARIS-SUD XI
asdc
ASI Science Data Center